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COMBINATORIAL PROOFS OF SOME ENUMERATION IDENTITIES

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(Received 8 April 1987)

We give a combinatorial proof of the following :

Theorem—The number of compositions of n is the same as the number of self-conjugate partitions with largest part equal to n .

Corollary—The number of n -reflected lattice paths equal twice the number of compositions of n . Some other enumeration identities are also proved.

1. INTRODUCTION

It is easily verified that the number of self-conjugate partitions of n with largest equal to m is the coefficient of $t^m q^n$ in

$$\sum_{m=0}^{\infty} \frac{t^m q^{m^2}}{(1 - tq^2)(1 - tq^4) \dots (1 - tq^{2m})}.$$

Hence the generating function for all self-conjugate partitions with largest part equal to m is what we get when we set $q = 1$:

$$\sum_{m=0}^{\infty} \frac{t^m}{(1 - t)^m} = \frac{1 - t}{1 - 2t}$$

or

$$\sum_{m=1}^{\infty} \frac{t^m}{(1 - t)^m} = \frac{t}{1 - 2t}. \quad \dots(1.1)$$

On the other hand, if $C_m(t)$ is the enumerating generating function for compositions with exactly m parts, then

$$C_m(t) = (t + t^2 + t^3 + \dots)^m = t^m (1 - t)^{-m}. \quad \dots(1.2)$$

And so the generating function with no restriction on the number or size of parts is

$$C(t) = \sum_{m=1}^{\infty} C_m(t) = \frac{t}{1 - 2t}. \quad \dots(1.3)$$

A comparison of (1.1) and (1.3) leads us to our main theorem.

Theorem—The number of composition of n is the same as the number of self-conjugate partitions with largest part equal to n .

The exact meaning of the theorem should be clear from the following example : There are eight compositions of 4, viz.

$$4, 31, 13, 2^2, 21^2, 121, 1^22, 1^4.$$

There are also eight self-conjugate partitions with largest part 4, viz.

$$41^3, 421^2, 4321, 43^21, 4^22^2, 4^232, 4^33, 4^4.$$

This paper is centered around a combinatorial proof of the main theorem. The n -reflected lattice paths of the corollary were recently studied by Agarwal and Andrews¹, and are defined as follows :

Definition—A lattice path from $(0, 0)$ to (n, n) is said to be n -reflected if for each (x, y) in the path $(n - y, n - x)$ is also in the path. For example, there are four 2-reflected lattice paths, viz.,

$$(0, 0), (1, 0), (2, 0), (2, 1), (2, 2); (0, 0), (1, 0), (1, 1), (2, 1), (2, 2);$$

$$(0, 0), (0, 1), (1, 1), (1, 2), (2, 2); (0, 0), (0, 1), (0, 2), (1, 2), (2, 2).$$

In the next section we shall prove some subsidiary theorems which are required in proving our main results combinatorially.

2. SUBSIDIARY THEOREMS

Theorem 2.1—The number of compositions of n with exactly m parts equals the number of partitions into m distinct parts with largest part n .

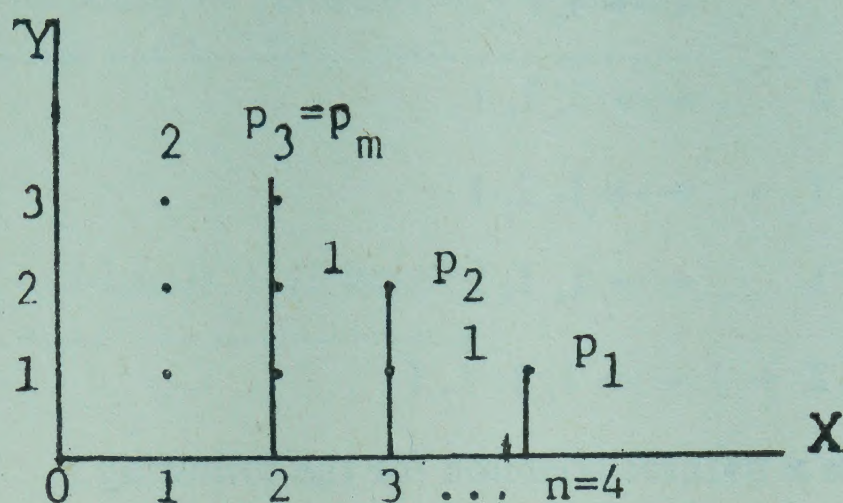
First proof (by generating function)—It is well known that the coefficient of $t^n q^N$ in

$$\frac{t^m q^{m(m+1)/2}}{(1-tq)(1-tq^2)\dots(1-tq^m)}$$

is the number of the partitions of N into m distinct parts with largest part n . Hence the generating function for all the partitions into m distinct parts with largest part n is what we get when we set $q = 1$, viz.,

$$\frac{t^m}{(1-t)^m},$$

and the theorem follows immediately by noting that this function also enumerates the compositions with exactly m parts [see eqn. (1.2)].



Second proof (combinatorial) —Let be the graph of a partition into m distinct parts with largest part n (In the above graph $n = 4$, $m = 3$; also note that the X -axis is drawn one unit of length below the last row and the Y -axis one unit of length to the left of the first column). We draw vertical lines from the corner point of each part and measure the distance of each line from its preceding one taking.

Y -axis also into consideration. We see that these distances give rise to a composition of n into exactly m parts. The correspondence being one-one the theorem is proved.

$$4 + 3 + 2 \longrightarrow 211$$

$$4 + 3 + 1 \longrightarrow 121$$

$$4 + 2 + 1 \longrightarrow 112$$

Theorem 2.2—The number of compositions of n is the same as the number of partitions into at most n distinct part with largest part n .

PROOF : Let $P(n, m)$ denote the number of partitions into m distinct parts with largest part n , and $C_{n,m}$ the number of compositions of n with exactly m parts. Then by Theorem 2.1, we have

$$C_{n,m} = P(n, m). \quad \dots(2.1)$$

Equation (2.1) implies

$$\sum_{m=1}^n C_{n,m} = \sum_{m=1}^n P(n, m),$$

and the theorem follows immediately.

The one-to-one correspondence established to prove Theorem 2.1 holds good here too.

$$4 \longleftrightarrow 4$$

$$4 + 3 \longleftrightarrow 3,1$$

$$4 + 2 \longleftrightarrow 2,2$$

$$\begin{aligned} 4 + 1 &\longleftrightarrow 1, 3 \\ 4 + 3 + 2 &\longleftrightarrow 2, 1, 1 \\ 4 + 3 + 1 &\longleftrightarrow 1, 2, 1 \\ 4 + 2 + 1 &\longleftrightarrow 1, 1, 2 \\ 4 + 3 + 2 + 1 &\longleftrightarrow 1, 1, 1, 1 \end{aligned}$$

Now we shall establish a natural bijection for the following :

Theorem 2.3—The number of self-conjugate partitions with largest part n is the same as the number of partitions into at most n distinct parts with largest part n .

We first define a k -bend.

Definition —We call a right-bend $\begin{smallmatrix} \dots\dots\dots \\ \vdots \end{smallmatrix}$, a k -bend if the number of dots in first row and first column are both equal to k . Thus by 1-bend we mean single dot., by 2-bend $\begin{smallmatrix} \dots \\ \vdots \end{smallmatrix}$ by 3-bend $\begin{smallmatrix} \dots\dots \\ \vdots \end{smallmatrix}$, etc.

Proof of the Theorem 2.3—Let $\pi = a_1 + a_2 + \dots + a_r$ ($a_1 > a_2 > \dots > a_r$) be a partition

We consider a graph which consists of r successive bends viz., a_1 -bend, a_2 -bend, ..., a_r -bend. We see immediately that this graph represents a self-conjugate partition with largest part equal to n . The correspondence being one-to-one, the theorem is proved.

Example—Consider the case $n = 4$.

Partitions into at most 4 distinct parts with largest part 4	Mapping	Self-conjugate partition with largest part 4
$4 + 3 + 2 + 1$	$(4\text{-bend}) + (3\text{-bend}) + (2\text{-bend}) + (1\text{-bend}).$ ←-----→	$\begin{smallmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{smallmatrix}$
$4 + 3 + 2$	$(4\text{-bend}) + (3\text{-bend}) + (2\text{-bend})$ ←-----→	$\begin{smallmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{smallmatrix}$
$4 + 3 + 1$	$(4\text{-bend}) + (3\text{-bend}) + (1\text{-bend})$ ←-----→	$\begin{smallmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{smallmatrix}$

$4 + 2 + 1$	$(4\text{-bend}) + (2\text{-bend}) + (1\text{-bend})$ ←-----→
		. . .
		. .
		.
$4 + 3$	$(4\text{-bend}) + (3\text{-bend})$ ←-----→
	
		. .
		. .
$4 + 2$	$(4\text{-bend}) + (2\text{-bend})$ ←-----→
		. . .
		. .
		.
$4 + 1$	$(4\text{-bend}) + (1\text{-bend})$ ←-----→
		. .
		.
		.
4	4-bend ←-----→
		.
		.
		.

3. PROOFS OF THE MAIN RESULTS

The bijections established to prove Theorems 2.2 and 2.3 together give rise a natural one-one onto mapping for our main theorem.

A bijection for the corollary can easily be obtained once we recall the following result due to Agarwal and Andrews¹.

Theorem 2.4—The n -reflected lattice paths are in one-to-one correspondence with the self-conjugate partitions with largest part $\leq n$.

4. CONCLUSION

Since a subset of $\{1, 2, \dots, n\}$ is also a partition into at most n distinct parts with largest part $\leq n$, the discussion of the preceding sections was a natural way to look at the following :

Theorem 4.1—Let A_n be the number of compositions of all integers $\leq n$. B_n the number of self-conjugate partitions with largest part $\leq n$. C_n the number of n -reflected lattice paths and D_n the number of subsets of $\{1, 2, \dots, n\}$.

Then

$$A_n = B_n = C_n = D_n = 2^n.$$

REFERENCE

1. A. K. Agarwal, and G. E. Andrews, *J. Stat. Pl. Innf.* **14**, (1986), 5-14.

A GENERALIZED VARIATIONAL INEQUALITY INVOLVING A GRADIENT

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In this paper we study a generalized variational inequality problem related to a certain general mathematical programming problem. Some existence theorems are established. Consequently, we obtain existence results and give bounds for optimal solutions of the programming problem.

1. INTRODUCTION

Given a continuous map $F: R^n \rightarrow R^n$, a continuous linear function $\psi: R^n \rightarrow R$, and a nonempty set K in R^n , the problem of finding $\bar{x} \in K$ such that

$$\langle F(\bar{x}), x - \bar{x} \rangle \geq \psi(\bar{x}) - \psi(x) \text{ for all } x \in K \quad \dots(1)$$

is called a variational inequality. Taking ψ as constant over the set K , we get a special case in which (1) becomes

$$\langle F(\bar{x}), x - \bar{x} \rangle \geq 0 \text{ for all } x \in K. \quad \dots(2)$$

Theory as well as applications of the variational inequality have been well documented in the literature (see. e. g. Cottle *et al.*³ and Kinderlehrer and Stampacchia⁴). In recent years, various extensions of this problem have been proposed and analyzed.

An important generalization of (2) is obtained by taking F to be a multifunction. In this case the problem is as follows: Given a multifunction V from R^n into itself, find vectors $\bar{x} \in K$ and $\bar{y}^* \in V(\bar{x})$ such that

$$\langle \bar{y}^*, x - \bar{x} \rangle \geq 0 \text{ for all } x \in K. \quad \dots(3)$$

It is known as the generalized variational inequality (see Chan and Pang² and references therein).

Many problems in mathematical programming can be reduced to variational inequalities and thus can be studied in the framework of variational inequality problems.

In particular, we have the following : Let f be a continuously differentiable convex function in R^n . Then the problem of finding \bar{x} in K such that

$$f(\bar{x}) = \min_{x \in K} f(x)$$

is equivalent to that of finding \bar{x} in K satisfying the variational inequality

$$\langle \nabla f(\bar{x}), x - \bar{x} \rangle \geq 0 \text{ for all } x \in K.$$

By using this fact, Mancino and Stampacchia⁵ showed that their algorithm developed for the variational inequality (2) is available for approximating optimal solution for a convex programming problem.

Let $\varphi(x, y)$ be a real-valued function defined on $X \times D$, where X and D are closed, convex sets in R^n and R^p , respectively. Consider now a nonlinear programming problem (P), and a saddle point problem (SPP) given as

$$(P) \min_{(x,y) \in U} \varphi(x, y),$$

where

$$U = \{(x, y) \in X \times D : \varphi(x, y) = \max_{\eta \in D} \varphi(x, \eta)\}$$

(SSP) : Find $x^0 \in X, y^0 \in D$ such that

$$\varphi(x^0, y) \leq \varphi(x^0, y^0) \leq \varphi(x, y^0)$$

for all $x \in X$ and $y \in D$. For a detailed study of these two problems, we see Mangasarian and Ponstein⁷.

Let $\varphi(x, y)$ be differentiable with respect to x for every fixed y , and let $\nabla_1(\cdot, \cdot)$ denote the gradient of φ with respect to the first vector variable. The variational inequality problem that can be associated with (SPP) is as follows : Find $\bar{x} \in X, y^* \in Y(\bar{x})$ such that

$$\langle \nabla_1 \varphi(\bar{x}, y^*), x - \bar{x} \rangle \geq 0 \text{ for all } x \in X \quad \dots(4)$$

where

$$Y(x) = \{y^* \in D : \varphi(x, y^*) = \max_{\eta \in D} \varphi(x, \eta)\}. \quad \dots(5)$$

It is easily seen that if $\varphi(g, y)$ is convex over X for every fixed $y \in D$, and (\bar{x}, y^*) is a solution of (4), then (\bar{x}, y^*) is also a solution of (SPP). Further, it follows from a lemma of Mangasarian and Ponstein⁷ (Lemma 3.4, p. 509) that any solution (\bar{x}, y) of (SPP) is an optimal solution of (P). Hence, the question of the existence of an optimal solution to (P) can be investigated via (4).

In this paper, we establish several existence theorems for (4) under various conditions on the map φ , each of which also guarantees the existence of an optimal solution of (P). Further, for (P), when it is solvable and φ is convex-concave over $X \times D$, we give simple bounds for all components of all optimal solutions.

2. MAIN RESULTS

Given a multifunction V from R^n into itself, V is said to be upper semicontinuous if a sequence $\{x^n\}$ converging to x , and a sequence $\{y^n\}$, with $y^n \in V(x)^n$, converging to y , implies $y \in V(x)$. Under this definition, the point-to-set map $x \mapsto Y(x)$ as given by (5) is upper semi-continuous. Clearly, $Y(x)$ is a closed set. In what follows, it is assumed that $Y(x)$ is nonempty and bounded. Thus, for every $x \in X$, $Y(x)$ is a compact subset of D .

The following result which will be needed in the proof of Theorem 2 is due to Parida and Sen¹⁰. Here, for a set C in R^p , $P(C)$ denotes the collection of all compact convex subsets of C .

Theorem 1—Let S be a compact convex set in R^n , and C a closed convex set in R^p . Let $V: S \rightarrow P(C)$ be upper semicontinuous and $M: S \times C \rightarrow R^n$ be continuous. Then there exist $\bar{x} \in S$, $\bar{y} \in V(\bar{x})$ such that

$$\langle M(\bar{x}, \bar{y}), x - \bar{x} \rangle \geq 0 \text{ for all } x \in S.$$

Theorem 2—Let $\phi(x, y)$ be a continuous convex-concave function over $X \times D$, and let $\phi(x, y)$ be continuously differentiable over X for every fixed $y \in D$. Further, assume that $Y(x)$ is nonempty and bounded. If there is a $\bar{u} \in X$ and a constant $r > \|\bar{u}\|$ such that

$$\max_{y^* \in Y(x)} \langle \nabla_1 \phi(x, y^*), \bar{u} - x \rangle \leq 0 \quad \dots(6)$$

for each $x \in X$ with $\|x\| = r$, then there exists a solution to (4), and hence an optimal solution to (P).

PROOF: Let $X_r = \{x \in X : \|x\| \leq r\}$. Clearly, X_r is compact and convex. Since $\phi(x, y)$ is concave in $y \in D$, $Y(x)$ is a compact and convex subset of D . It follows from Theorem 1 that there exist $\bar{x} \in X_r$, $\bar{y}^* \in Y(\bar{x})$ such that

$$\langle \nabla_1 \phi(\bar{x}, \bar{y}^*), x - \bar{x} \rangle \geq 0 \text{ for all } x \in X_r. \quad \dots(7)$$

We distinguish two cases.

Case 1— $\|\bar{x}\| < r$. Given $x \in X$, we can choose $0 < \lambda < 1$ small enough so that $w = \lambda x + (1 - \lambda)\bar{x}$ lies in X_r . Then it follows from (7) that

$$\begin{aligned} 0 &\leq \langle \nabla_1 \phi(\bar{x}, \bar{y}^*), w - \bar{x} \rangle \\ &= \lambda \langle \nabla_1 \phi(\bar{x}, \bar{y}^*), x - \bar{x} \rangle + (1 - \lambda) \langle \nabla_1 \phi(\bar{x}, \bar{y}^*), \bar{x} - \bar{x} \rangle, \\ &= \lambda \langle \nabla_1 \phi(\bar{x}, \bar{y}^*), x - \bar{x} \rangle \end{aligned}$$

and consequently, (\bar{x}, \bar{y}^*) satisfies (4).

Case 2— $\|x\| = r$. Since $\bar{u} \in X_r$, it follows from (6) and (7) that $\langle \nabla_1 \phi(\bar{x}, \bar{y}^*), \bar{u} - \bar{x} \rangle = 0$. Since $\|\bar{u}\| < r$, for any given $x \in X$, again we can choose

$0 < \lambda < 1$ small enough so that $w' = \lambda x + (1 - \lambda) \bar{u}$ lies in X_r . Then, proceeding as in Case 1, it can be shown that (\bar{x}, \bar{y}^*) satisfies (4). Therefore, we have

$$\langle \nabla_1 \varphi(\bar{x}, \bar{y}^*), x - \bar{x} \rangle \geq 0 \text{ for all } x \in X. \quad \dots(8)$$

Now, from (5), (8) and the convexity of $\varphi(x, \bar{y}^*)$ over X , we get

$$\varphi(x, \bar{y}^*) \geq \varphi(\bar{x}, \bar{y}^*) \text{ for all } x \in X$$

$$\max_{\eta \in D} \varphi(\bar{x}, \eta) = \varphi(\bar{x}, \bar{y}^*),$$

which implies that (\bar{x}, \bar{y}^*) solves (SPP). Finally, it follows from Lemma 3.4, p. 509 of Mangasarian and Ponstein⁷ that (\bar{x}, \bar{y}^*) is an optimal solution of (P). which implies that (\bar{x}, \bar{y}^*) is an optimal solution of (P).

The proof of Theorem 2 shows that the following result also holds.

Theorem 3—Let $\varphi(x, y)$ be a continuous convex-concave function over $X \times D$, and let $\varphi(x, y)$ be continuously differentiable over X for every fixed $y \in D$. Further, assume that $Y(x)$ is nonempty and bounded. If for some real number $r > 0$, the solution of the variational inequality

$$\bar{x} \in X_r, \bar{y}^* \in Y(\bar{x})$$

$$\langle \nabla_1 \varphi(\bar{x}, \bar{y}^*), x - \bar{x} \rangle \geq 0 \text{ for all } x \in X_r$$

(which certainly has solutions) satisfies the estimate $\|\bar{x}\| < r$, then there exists a solution to (4), and hence an optimal solution to (P).

Now we consider some special mappings of interest in applications and show that condition (6) of Theorem 2 is satisfied for these mappings. The definitions we give extend the concept of nontonicity for single-valued functions (see Minty⁸) to multi-valued functions.

A multifunction $V: K \rightarrow R^n$ is said to be monotone on K if for every pair of vectors $x, u \in K$

$$\langle y^* - v^*, x - u \rangle \geq 0 \text{ for all } y^* \in V(x), v^* \in V(u).$$

The map V is called strictly monotone if for every pair of vectors $x, u \in K, x \neq u$.

$$\langle y^* - v^*, x - u \rangle > 0 \text{ for all } y^* \in V(x), v^* \in V(u).$$

Proposition 1—Let $\varphi: R^n \times R^p \rightarrow R$ be continuously differentiable over X for every fixed $y \in D$. If $\varphi(x, y)$ is convex in $x \in X$, then the multifunction $x \mapsto \{\nabla_1 \varphi(x, y^*): y^* \in Y(x)\}$ is monotone on X .

PROOF : From convexity of $\varphi(x, \cdot)$ over X , we have

$$\varphi(x, v^*) - \varphi(u, v^*) \geq \langle \nabla_1 \varphi(u, v^*), x - u \rangle$$

$$\varphi(u, y^*) - \varphi(x, y^*) \geq \langle \nabla_1 \varphi(x, y^*), u - x \rangle$$

for every $y^* \in Y(x)$ and $v^* \in Y(u)$. By the definition of $Y(x)$, we have

$$\varphi(x, y^*) - \varphi(u, v^*) \geq \varphi(x, v^*) - \varphi(u, v^*)$$

$$\varphi(u, v^*) - \varphi(x, y^*) \geq \varphi(u, y^*) - \varphi(x, y^*).$$

Now, by adding the above four inequalities, it is seen that the map $x \mapsto \{\nabla_1 \varphi(x, y^*) : y^* \in Y(x)\}$ is monotone on X .

If F is strictly monotone on K , then (2) has, at most, one solution. To see this, let both \bar{x} and \bar{y} be solutions to (2) with $\bar{x} \neq \bar{y}$. Then

$$\begin{aligned} 0 &< \langle F(\bar{x}) - F(\bar{y}), \bar{x} - \bar{y} \rangle \\ &= -\langle F(\bar{x}), \bar{y} - \bar{x} \rangle - \langle F(\bar{y}), \bar{x} - \bar{y} \rangle \\ &\leq 0 \end{aligned}$$

a contradiction. Using arguments similar to this and the conclusion of Proposition 1, it can be shown that (P) has, at most, one optimal solution if $\varphi(x, y)$ is strictly convex in $x \in X$ for every fixed $y \in D$.

In the following theorem, we take X to be a pointed convex cone. The polar of the cone X is given by

$$X^* = \{y \in R^n : \langle x, y \rangle \geq 0 \text{ for all } x \in X\}.$$

Theorem 4—Let X be a pointed closed convex cone in R^n , and let $\varphi(x, y)$ be as in Theorem 3. Suppose that $Y(x)$ is nonempty and bounded for every $x \in X$. If there is a $\bar{u} \in X$ and a $\bar{v}^* \in Y(\bar{u})$ such that $\nabla_1 \varphi(\bar{u}, \bar{v}^*) \in \text{int } X^*$, then (4) has a solution, and hence, (P) has an optimal solution.

PROOF: We denote $p = \nabla_1 \varphi(\bar{u}, \bar{v}^*)$. Since $p \in \text{int } X^*$, the set $B = \{x \in X : p^T(x - \bar{u}) \leq 0\}$ is compact, and consequently, for all $x \in X \setminus B$, $p^T(x - \bar{u}) > 0$. This implies that there is a constant $r > \|\bar{u}\|$ such that $p^T(x - \bar{u}) > 0$ for all $x \in X$ with $\|x\| = r$. From the convexity of φ and Proposition 1, it follows that the map $x \mapsto \{\nabla_1 \varphi(x, y^*) : y^* \in Y(x)\}$ is monotone. Hence, for any $x \in X$ with $\|x\| = r$, we have

$$\begin{aligned} \langle \nabla_1 \varphi(x, y^*), x - \bar{u} \rangle &\geq \langle \nabla_1 \varphi(\bar{u}, \bar{v}^*), x - \bar{u} \rangle \\ &= p^T(x - \bar{u}) \\ &> 0 \end{aligned}$$

for all $y^* \in Y(x)$. This shows that condition (6) of Theorem 2 is satisfied. Therefore, (4) has a solution and consequently, (P) has an optimal solution.

Following the same reasoning used by Mangasarian and McLinden⁶, and Parida and Sen⁹ for providing numerical bounds for optimal solutions of convex programs we obtain the following result for (P).

Theorem 5—Let $X = R_+^n$ and let $\varphi(x, y)$ be a continuous convex-concave function over $R_+^n \times D$. Further, let $\varphi(x, y)$ be continuously differentiable over R_+^n for every fixed $y \in D$. Suppose that $Y(x)$ is nonempty and bounded for every $x \in R_+^n$. If there is a $\bar{u} \geq 0$ and a $\bar{v}^* \in Y(\bar{u})$ such that $\nabla_1 \varphi(\bar{u}, \bar{v}^*) > 0$, then there exists (\bar{x}, \bar{y}^*) which solves (P). Any such solution is bounded as follows :

$$\|\bar{x}\|_1 \leq \langle \nabla_1 \varphi(\bar{u}, \bar{v}^*), \bar{u} \rangle / \min_{1 \leq i \leq n} \{\nabla_1 \varphi(\bar{u}, \bar{v}^*)\}_i. \quad \dots(9)$$

PROOF : The existence part follows from Theorem 4. To get the bound (9), let (\bar{x}, \bar{y}^*) be an optimal solution of (P). Since (\bar{x}, \bar{y}^*) is also a solution of (4), we have

$$\langle \nabla_1 \varphi(\bar{x}, \bar{y}^*), \bar{u} - \bar{x} \rangle \geq 0.$$

From the convexity of $\varphi(x, y)$ and Proposition 1, we have

$$\langle \nabla_1 \varphi(\bar{u}, \bar{v}^*) - \nabla_1 \varphi(\bar{x}, \bar{y}^*), \bar{u} - \bar{x} \rangle \geq 0.$$

Now, from these two inequalities, it follows that

$$\begin{aligned} \langle \nabla_1 \varphi(\bar{u}, \bar{v}^*), \bar{u} \rangle &\geq \langle \nabla_1 \varphi(\bar{u}, \bar{v}^*), \bar{x} \rangle \\ &\geq \min_{1 \leq i \leq n} \{\nabla_1 \varphi(\bar{u}, \bar{v}^*)\}_i \cdot \sum_{i=1}^n \bar{x}_i \\ &= \min_{1 \leq i \leq n} \{\nabla_1 \varphi(\bar{u}, \bar{v}^*)\}_i \cdot \|\bar{x}\|_1. \end{aligned}$$

This completes the proof of the theorem.

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CHARACTERIZATIONS OF EXTREMALLY DISCONNECTED SPACES

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In this note, the author obtains several characterizations of extremally disconnected spaces by utilizing preopen sets and semi-preopen sets.

1. INTRODUCTION

Quite recently, Sivaraj⁹ has obtained some characterizations of extremally disconnected spaces by utilizing semi-open sets due to Levine⁶. Mashhour *et al.*⁷ have defined preopen sets. Recently, Andrijević¹ has introduced a new class of sets, called semi-preopen sets, in topological spaces. The class of semi-preopen sets contains both the class of semi-open sets and the class of preopen sets. The purpose of this note is to obtain several characterizations of extremally disconnected spaces by utilizing preopen sets and semi-preopen sets.

2. PRELIMINARIES

Throughout the present note, by X we denote a topological space. Let A be a subset of X . The closure of A and the interior of A are denoted by $\text{Cl}(A)$ and $\text{Int}(A)$, respectively. A subset A is said to be preopen⁷ if $A \subset \text{Int}(\text{Cl}(A))$. A subset A is called semi-open⁶ (resp. semi-preopen¹) if there exists an open (resp. preopen) set U of X such that $U \subset A \subset \text{Cl}(U)$. Abd El-Monsef *et al.*⁸ have introduced a weak form of open sets called β -open sets. The notion of β -open sets is equivalent to that of semi-preopen sets. In this note, we utilize the term "semi-preopen". The family of all preopen (resp. semi-open, semi-preopen) sets of X is denoted by $PO(X)$ (resp. $SO(X)$, $SPO(X)$). Levine⁶ (resp. Andrijević¹) showed that a subset A of X is semi-open (resp. semi-preopen) if and only if $A \subset \text{Cl}(\text{Int}(A))$ (resp. $A \subset \text{Cl}(\text{Int}(\text{Cl}(A)))$). These characterizations will be frequently utilized in the sequel.

The complement of a semi-open set is called semi-closed³. The intersection of all semi-closed sets containing a subset A of X is called the semi-closure³ of A and is denoted by $\text{sCl}(A)$. It is obvious that $\text{sCl}(A)$ is semi-closed. A point x of X is said to be a θ -adherent¹⁰ (resp. δ -adherent) point of A if $A \cap \text{Cl}(U) \neq \emptyset$ (resp. $A \cap \text{Int}(\text{Cl}(U)) \neq \emptyset$) for every open set U containing x . The set of all θ -adherent (resp. δ -adherent) points of A is called the θ -closure (resp. δ -closure) of A and is denoted by $\text{Cl}_\theta(A)$ (resp. $\text{Cl}_\delta(A)$).

The following lemma is shown by Janković⁵ but we shall give another proof.

*Lemma 2.1*⁵—If $A \in PO(X)$, then $Cl(A) = Cl_\delta(A) = Cl_\theta(A)$.

PROOF : It is obvious that $Cl(S) \subset Cl_\delta(S) \subset Cl_\theta(S)$ for every subset S of X . Thus, it remains to show that $Cl_\theta(A) \subset Cl(A)$. Assume that $x \notin Cl(A)$, then $U \cap A = \phi$ for some open set U containing x . We have $U \cap Cl(A) = \phi$ and hence $Cl(U) \cap Int(Cl(A)) = \phi$. Since $A \in PO(X)$, we obtain $Cl(U) \cap A = \phi$. This shows that $x \in X - Cl_\theta(A)$. Consequently, we have $Cl_\theta(A) \subset Cl(A)$ and $Cl(A) = Cl_\delta(A) = Cl_\theta(A)$.

Sivaraj⁹ showed that $Cl(A) = Cl_\delta(A)$ for every $A \in SO(X)$. The following lemma is an improvement of this result.

Lemma 2.2—If $A \in SPO(X)$, then $Cl(A) = Cl_\delta(A)$.

PROOF : We show that $Cl_\delta(A) \subset Cl(A)$ since the opposite inclusion is obvious. Assume that $x \in X - Cl(A)$, then $U \cap A = \phi$ for some open set U containing x . Since U is open, $Cl(U) \cap Int(Cl(A)) = \phi$ and hence we have $Int(Cl(U)) \cap Cl(Int(Cl(A))) = \phi$. Moreover, since $A \in SPO(X)$, we obtain $Int(Cl(U)) \cap A = \phi$. This shows that $x \in X - Cl_\delta(A)$. Therefore, we have $Cl_\delta(A) \subset Cl(A)$ and hence $Cl(A) = Cl_\delta(A)$.

3. CHARACTERIZATIONS OF EXTREMALLY DISCONNECTED SPACES

A topological space X is called extremally disconnected (briefly E. D.) if $Cl(U)$ is open in X for every open set U of X , or, equivalently if every two disjoint open sets of X have disjoint closures.

Theorem 3.1—The following are equivalent for a space X .

- (a) X is E. D.
- (b) The closure of every semi-preopen set of X is open.
- (c) The δ -closure of every semi-preopen set of X is open.
- (d) The δ -closure of every preopen set of X is open.
- (e) The β -closure of every preopen set of X is open.
- (f) The closure of every preopen set of X is open.

PROOF : This follows immediately from Lemmas 2.1 and 2.2 since $Cl(A) = Cl(Int(Cl(A)))$ for every $A \in SPO(X)$ and $PO(X) \subset SPO(X)$.

Janković⁵ showed that if a space X is E. D. then $sCl(A) = Cl_\theta(A)$ for every $A \in PO(X) \cup SO(X)$. We show that the converse is also true.

Theorem 3.2—The following are equivalent for a space X .

- (a) X is E. D.
- (b) $sCl(A) = Cl_\theta(A)$ for every $A \in PO(X) \cup SO(X)$
- (c) $sCl(A) = Cl(A)$ for every $A \in SPO(X)$.
- (d) $sCl(A) = Cl_\delta(A)$ for every $A \in SPO(X)$.

PROOF : (a) \Rightarrow (b) : This is shown in Corollaries 4.5 and 4.6 of Janković⁵
 (b) \Rightarrow (a) : First, let A be any preopen set of X . By Proposition 2.7 of Janković⁵ and Lemma 2.1, we have $Int(Cl(A)) = sCl(A) = Cl_\theta(A) = Cl(A)$. Therefore, $Cl(A)$ is open in X and hence it follows from Theorem 3.1 that X is E. D. Next, let A be any semi-open set of X . We have $sCl(A) \subset Cl(A) \subset Cl_\theta(A) = sCl(A)$ and hence $sCl(A) = Cl(A)$. Therefore, it follows from Theorem 2.1 of Sivaraj⁹ that X is E. D.

(a) \Rightarrow (c) : It follows from Lemma 2.6 of Janković⁵ that for every subset S of X , $Int(Cl(S)) \subset sCl(S) \subset Cl(S)$. Since X is E. D., by Theorem 3.1, $Cl(A)$ is open in X for every $A \subset SPO(X)$. Therefore, we have $sCl(A) = Cl(A)$ for every $A \in SPO(X)$. Therefore, we have $sCl(A) = Cl(A)$ for every $A \in SPO(X)$.

(c) \Rightarrow (d) : This is an immediate consequence of Lemma 2.2.

(d) \Rightarrow (a) : Let U, V be any disjoint open sets. Then we have $sCl(U) \cap V = \phi$. Since $sCl(U) \in SO(X)$, we have $sCl(U) \cap sCl(V) = \phi$. By Lemma 2.2, we obtain $Cl(U) \cap Cl(V) = \phi$. This shows that X is E. D.

Theorem 3.3—The following are equivalent for a space X .

- (a) X is E. D.
- (b) If $A \in SPO(X)$, $B \in SO(X)$ and $A \cap B = \phi$, then $Cl(A) \cap Cl(B) = \phi$,
- (c) If $A \in SPO(X)$, $B \in SO(X)$ and $A \cap B = \phi$, and $Cl_\delta(A) \cap Cl_\delta(B) = \phi$,
- (d) If $A \in PO(X)$, $B \in SO(X)$ and $A \cap B = \phi$, then $Cl_\theta(A) \cap Cl_\delta(B) = \phi$,
- (e) If $A \in PO(X)$, $B \in SO(X)$ and $A \cap B = \phi$, then $Cl(A) \cap Cl(B) = \phi$.

PROOF : (a) \Rightarrow (b) : Suppose that $A \in SPO(X)$, $B \in SO(X)$ and $A \cap B = \phi$. We have $Cl(A) \cap Int(B) = \phi$. By Theorem 3.1, $Cl(A)$ is open in X and hence $Cl(A) \cap Cl(B) = Cl(A) \cap Cl(Int(B)) = \phi$ since $B \in SO(X)$.

(b) \Rightarrow (c), (c) \Rightarrow (d) and (d) \Rightarrow (e): These follow easily from Lemmas 2.1 and 2.2.

(e) \Rightarrow (a) : This is obvious since every open set is preopen and semi-open.

Remark 3.4 : Extremal disconnectedness of a topological space cannot be characterized by the statement that every two disjoint preopen sets have disjoint closures. There exists an E. D. space not satisfying the statement.

*Example 3.5*²—Let $X = \{a, b, c\}$ and $\tau = \{\phi, X, \{a, b\}\}$. Then the space (X, τ) is E. D., $\{a\}, \{b\} \in PO(X)$, and $Cl(\{a\}) \cap Cl(\{b\}) \neq \phi$.

Theorem 3.6—The following are equivalent for a space X .

- (a) X is E. D.
- (b) If $A \in SO(X)$ and $B \in SPO(X)$, then $Cl(A) \cap Cl(B) = Cl(A \cap B)$.
- (c) If $A \in SO(X)$ and $B \in SPO(X)$, then $A \cap B \in SPO(X)$.

PROOF : First, we recall the fact that if U is open in X then $U \cap Cl(S) \subset Cl(U \cap S)$ for every subset S of X .

(a) \Rightarrow (b) : Let $A \in SO(X)$ and $B \in SPO(X)$. By Theorem 3.1, $Cl(B)$ is open in X and we obtain

$$Cl(A) \cap Cl(B) = Cl(Int(A)) \cap Cl(B) \subset Cl(Int(A) \cap Cl(B)) \subset Cl(A \cap B).$$

Therefore, we have $Cl(A) \cap Cl(B) = Cl(A \cap B)$.

(b) \Rightarrow (c) : Let $A \in SO(X)$ and $B \in SPO(X)$. Then, we have

$$\begin{aligned} A \cap B &\subset Cl(Int(A)) \cap Cl(Int(Cl(B))) = Cl(Int(A) \\ &\cap Int(Cl(B))) = Cl(Int(A \cap Cl(B))) \subset Cl(Int(Cl(A) \\ &\cap Cl(B))) = Cl(Int(Cl(A \cap B))). \end{aligned}$$

This shows that $A \cap B \in SPO(X)$.

(c) \Rightarrow (a) : It is enough to show $Cl(A) \cap Cl(B) = Cl(A \cap B)$ for all open sets A and B . Let A and B be any open sets of X . Then, $Cl(A)$ and $Cl(B)$ are semi-open and hence $Cl(A) \cap Cl(B) \in SPO(X)$. Therefore, we have

$$\begin{aligned} Cl(A) \cap Cl(B) &\subset Cl(Int(Cl(A) \cap Cl(B))) = Cl(Int(Cl(A) \\ &\cap Int(Cl(B)))) \subset Cl(Cl(A) \cap Int(Cl(B))) \subseteq Cl(A \\ &\cap Int(Cl(B))) \subset Cl(A \cap Cl(B)) \subset Cl(A \cap B). \end{aligned}$$

Consequently, we obtain $Cl(A) \cap Cl(B) = Cl(A \cap B)$.

Remark 3.7 : Janković⁴ showed that a space X is E. D. if and only if $A \cap B \in SO(X)$ for every $A, B \in SO(X)$. However, neither $PO(X)$ nor $SPO(X)$ can substitute for $SO(X)$ in this result. Because, in the space (X, τ) of Example 3.5 (X, τ) is

E. D. and $\{a, c\}, \{b, c\} \in PO(X, \tau)$, however $\{c\} = \{a, c\} \cap \{b, c\}$ is not contained in $SPO(X, \tau)$.

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SPLITTINGS OF ABELIAN GROUPS BY INTEGERS

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A finite subset M of non-zero integers is said to split a finite abelian additive group G , if there exists a set S in G such that each non-zero element of G has a unique representation in the form ms , $m \in M$ and $s \in S$ and O has no such representation. For the set $S(k) = [1, 2, \dots, k]$ for $k \leq 700$, except $k = 24, 60, 62, 84, 144, 171, 180, 264, 312, 420, 480, 665, 684$, it is proved that if $S(k)$ splits $C(r) \times G$ for a finite abelian group G and cyclic group $C(r)$ of order r , with $r \equiv 1 \pmod{k}$, then $S(k)$ splits $C(r)$. Stein asked this question for all k . Our result gives a partial answer to his question.

1. INTRODUCTION

Let M be a finite set of non-zero integers, called a multiplier set, and let G be a finite abelian additive group. Assume that there is a set S in G such that each non-zero element in G has a unique representation in the form ms , $m \in M$, $s \in S$ and that O has no such representation. Then M is said to split G and S is called a splitting set. Splittings were first considered by Stein⁴.

If $(m, |G|) = 1$ for each $m \in M$, the splitting is called non-singular. Otherwise it is called singular. If each prime that divides $|G|$ divides at least one $m \in M$, then the splitting is called purely singular (see Stein⁵ for more details).

Hickerson has conjectured that if the set $S(k) = [1, 2, \dots, k]$ splits a finite abelian group G purely singularly, then G must be either $C(1)$, $C(k+1)$, or $C(2k+1)$, where $C(r)$ denotes the cyclic group of order r .

Stein⁵ observed that for $k = 2, 3, 4, 6$, and 8 if the set $S(k)$ splits $G_1 = G \times C(r)$ for a finite abelian group G , then $S(k)$ splits $C(r)$ provided that $r \equiv 1 \pmod{k}$ and posed the question⁵ (Question IV₋₁) for other values of k . In this connection we prove:

Theorem 1—If $S(k)$ splits $G_1 = G \times C(r)$ where G is a finite abelian group, $r \equiv 1 \pmod{k}$, and k satisfies Hickerson's conjecture, then $S(k)$ splits $C(r)$.

Hickerson³ has proved the conjecture for $k \leq 700$ with exceptions $k = 24, 60, 62, 84, 144, 171, 180, 264, 312, 420, 480, 665$, and 684 . Thus in view of Theorem 1, Stein's assertion is true for the values of $k \leq 700$, except perhaps the ones listed above.

2. SOME KNOWN RESULTS

For the proof of Theorem 1 we make use of the following results.

Lemma 1—Let $G - [0] = M$. S be a splitting of a finite abelian group G . Then there exist subgroups H and K of G such that

- (i) $G = H \times K$
- (ii) M splits H non-singularly
- (iii) M splits K purely singularly.

Further H and K are uniquely determined by these conditions.

This result is due to Hickerson² (Theorem 1.2.5). The proof shows that if P denotes the set of prime divisors of $|G|$ which are relatively prime to all elements of M then the subgroup H is the direct product of p -syllow subgroups of G where $p \in P$ and K is the direct product of p -syllow subgroups of G for $p \notin P$.

The converse of the above is true, i. e. if H and K are finite abelian groups such that M splits H non-singularly and M splits K purely singularly then M splits $H \times K$. In fact the following more general result follows from Theorem of Hamaker and Stein¹.

Lemma 2—Let H be a subgroup of the finite abelian group G . Suppose M splits both H and G/H and that the splitting of H is non-singular. Then M splits G .

The following result, which is a consequence of Lemma 1, Lemma 2 and a results due to Hamaker and Stein¹ (Theorem 4) reduces the study of splittings of a finite abelian group G to the case of non-singular splittings of cyclic groups $C(p)$ of prime orders and the purely singular splittings.

Lemma 3—Let G be a finite abelian group, M a set of positive integers, P the set of prime divisors p of $|G|$ such that $(p, m) = 1$ for all $m \in M$ and K the subgroup of G obtained by taking the direct product of all the p -syllow subgroups of G for $p \notin P$. Then M splits G if and only if M splits $C(p)$ for all $p \in P$ and M splits K .

3. PROOF OF THEOREM 1

Let $r = p_1^{\alpha_1} \dots p_s^{\alpha_s} p_1^{\beta_1} q_t^{\beta_t}$ be the prime factorization of r where the primes $p_i, 1 \leq i \leq s$ are $\leq k$ and primes $q_j, 1 \leq j \leq t$ are $> k$.

Since $S(k)$ splits $C(r) \times G$, by Lemma 3, it splits $C(q_j)$ and hence $q_j \equiv 1 \pmod{k}$, for $1 \leq j \leq t$ so that

$$r_1 = p_1^{\alpha_1} \dots p_s^{\alpha_s} \equiv 1 \pmod{k}. \quad \dots(1)$$

Let $G_1 = H_1 \times K_1$ where H_1 and K_1 are uniquely determined by Lemma 1 such that

$S(k)$ splits H_1 non-singularly and K_1 purely singularly. Since k satisfies Hickerson's conjecture it follows that

$$K_1 = C(1) \text{ or } C(k+1) \text{ or } C(2k+1). \quad \dots(2)$$

Since K_1 is the direct product of the p -syllow subgroups of G_1 , where p runs over all prime divisors of $|G_1| = r |G|$ with $p \leq k$, we have

$$r_1 \mid |K_1|. \quad \dots(3)$$

It follows from (1), (2) and (3) that

either (i) $r_1 = 1$ or (ii) $K_1 = C(r_1)$.

Case (i)—In this case we have $r = q_1^{\beta_1} \dots q_t^{\beta_t}$ and since $S(k)$ splits $C(q_j)$, for $1 \leq j \leq t$, by Lemma 3, $S(k)$ splits $C(r)$.

Case (ii)— In this case we have $K_1 = C(r_1)$.

Let $r_2 = q_1^{\beta_1} \dots q_t^{\beta_t}$ so that $C(r) = K_1 \times C(r_2)$.

Now since $S(k)$ splits $C(r_2)$ non-singularly as in case (i) and $S(k)$ splits K_1 by Lemma 2 it follows that $S(k)$ splits $C(r)$. This completes the proof.

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COHOMOLOGY AND REDUCIBILITY OF REPRESENTATIONS OF SEMISIMPLE Γ -GRADED LIE ALGEBRAS

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The invariant forms, in particular, the bilinear Cartan-Killing form is considered. Casimir invariants are determined for nondegenerate Γ GLA and the cohomology of a wide class of representations of semisimple Γ GLA is shown to vanish. Finally, the applications to reducibility of representations are discussed.

INTRODUCTION

Cohomological techniques have played a significant role in describing anomalies and renormalisability in quantum field theory, e.g., it was recognised by Becchi, *et al.*¹ that chiral anomalies belong to nontrivial cohomological classes associated with a gauge invariant classical action. Trace anomalies² too are characterised by nontrivial cohomological classes for a system having local Weyl symmetry. It was noted by Stora³ that renormalisability of quantum field theory is associated with the triviality of the second cohomology of the BRS algebras. We will specially address ourselves to the cohomology properties (algebraic) of graded Lie algebras in the context of their structure. The Z_2 -graded Lie algebras (popularly known as super Lie algebras) and the classification of the classical Lie super algebras were systematically developed by several authors especially Kac^{4,7}. Attempts have been made to obtain the Iwasawa and Langlands decompositions of such super Lie algebras and the various parabolic subalgebras are determined⁸. It is hoped that Schmidt induction scheme could be carried out to obtain the various irreducible representations of Z_2 -graded Lie algebras.

In a previous communication⁹, we had introduced the cohomology of Z_2 -graded Lie algebras and subsequently it was extended to generalised Lie algebras (Γ GLA), also called color superalgebras. It was shown that the cohomology of certain representations of a broad class of GLA is trivial⁸. In the present communication, we analyse the properties of invariant forms to obtain the cohomology properties of nondegenerate Γ GLA's. The results are then used to study the reducibility of finite dimensional representations of semisimple Γ GLA's. In so doing, we generalise our definition of the coboundary operator.

The plan of the paper is as follows. In section 2, we introduce the basic concepts of Γ GLA and relate the structure of a Γ GLA to that of a graded Lie algebra with com-

mutation factor $\epsilon(\alpha, \beta)$ instead of the usual $(-1)^{\alpha\beta}$. Following Backhouse¹¹ we define the invariant forms and establish their symmetry properties, in particular, we obtain the bilinear Cartan-Killing form $K(l, m)$. In section 3, we obtain the Casimir invariants of a nondegenerate Γ GLA defined as one in which $\det K(l, m) \neq 0$ ^{12,13}. We also introduce the notion of a Γ graded ideal and make a few remarks on the structure of a nondegenerate Γ GLA. We also show that all derivations of a nondegenerate Γ GLA are inner. It may be noted that the invariant forms and Casimir invariants constructed in these sections are important examples of more general invariant forms constructed earlier^{14,15}. However, the results and the methods used are useful for subsequent computations and have been expatiated for the sake of completeness.

In section 4, we find the class of representations of semisimple GLA for which the cohomology is trivial, proving a generalised version of Whitehead's lemma. Finally in section 5, Weyl's reducibility theorem for Lie algebras is generalised to Γ GLA. The notation used throughout is same as in Mitra and Tripathy¹⁰. Also \mathcal{F} throughout characterised a field of characteristic zero.

2. RESUME AND INVARIANT FORMS OF Γ GLA

In this section, we begin by giving a short 'resume' of Γ GLA. We relate the structure of a Γ GLA to that of a GLA with commutation factor $\epsilon(\alpha, \beta)$ instead of the usual $(-1)^{\alpha\beta}$. Finally, we obtain the invariant forms of order n and demonstrate their invariance and symmetry properties.

(A) Resume of Γ Graded Algebras

The following definitions are well known from the theory of Γ GLA (ref. 7) and are given below for the sake of completeness.

Definition 1—A vector space V is said to be Γ graded if we are given a family $(V_\gamma)_{\gamma \in \Gamma}$ of subspaces of V such that V is the direct sum

$$V = \bigoplus_{\gamma \in \Gamma} V_\gamma, \quad \dots(2.1)$$

Γ being an Abelian group (see Definition 4). An element of V is said to be homogeneous of degree $\gamma \in \Gamma$ if it is an element of V_γ . A subspace V' of V is said to be Γ graded if $V' = \bigoplus_{\gamma \in \Gamma} (V' \cap V_\gamma)$.

Definition 2—An algebra S is called Γ graded if its underlying vector space is Γ graded

$$S = \bigoplus_{\gamma \in \Gamma} S_\gamma \quad \dots(2.2a)$$

and if $S_\alpha S_\beta \subset S_{\alpha+\beta} \forall \alpha, \beta \in \Gamma$.

If S has a unit element e , it follows that $e \in S_0$. A subalgebra S' is said to be Γ graded if it is Γ graded as a subspace of S .

Definition 3—A commutation factor on Γ is a mapping $\epsilon : \Gamma \otimes \Gamma \rightarrow K$, K being a commutative field so that

$$(1) \quad \epsilon(\alpha, \beta) \epsilon(\beta, \alpha) = 1 \quad \dots(2.3a)$$

$$(2) \quad \epsilon(\alpha, \beta + \gamma) = \epsilon(\alpha, \beta) \epsilon(\alpha, \gamma) \quad \dots(2.3b)$$

$$(3) \quad \epsilon(\alpha + \beta, \gamma) = \epsilon(\alpha, \gamma) \epsilon(\beta, \gamma) \text{ for all } \alpha, \beta, \gamma \in \Gamma. \quad \dots(2.3c)$$

Definition 4—Let Γ be an Abelian group and let ϵ be a commutation factor on Γ . A Γ graded Algebra

$$L = \bigoplus_{\gamma \in \Gamma} L_\gamma \quad \dots(2.4)$$

whose product mapping is denoted by an angle bracket $\langle \rangle$ is called a Γ graded Lie Algebra, or simply a Γ graded Lie Algebra (Γ GLA) if the following properties are satisfied.

$$(1) \quad \langle A, B \rangle = -\epsilon(\alpha, \beta) \langle B, A \rangle \text{ } (\epsilon \text{ skew symmetry}) \quad \dots(2.5a)$$

$$(2) \quad \epsilon(\gamma, \alpha) \langle A, \langle B, C \rangle \rangle + \text{cyclic permutations} = 0 \\ (\epsilon \text{ Jacobi identity}) \quad \dots(2.5b)$$

for all $A \in L_\alpha, B \in L_\beta, C \in L_\gamma, \forall \alpha, \beta, \gamma \in \Gamma$.

When Γ consists of the abelian group $(0, 1)$ under the addition operation, and the commutation factor $\epsilon(\alpha, \beta)$ is chosen to be $(-1)^{\alpha\beta}$, L is a Graded Lie Algebra (Lie superalgebra) and

$$\langle L_0, L_0 \rangle \subset L_0, \langle L_0, L_1 \rangle \subset L_2, \langle L_1, L_1 \rangle \subset L_0 \quad \dots(2.6)$$

while the ϵ Jacobi identity reduces to the form

$$\langle \langle A, B \rangle, C \rangle = \langle A, \langle B, C \rangle \rangle - (-1)^{\alpha\beta} \langle B, \langle A, C \rangle \rangle. \quad \dots(2.7)$$

(B) *Structure of a Γ GLA*

Given a Γ GLA L , as in (2.4), let,

$$\Gamma_0 = \{\alpha \in \Gamma : \epsilon(\alpha, \alpha) = +1\} \quad \dots(2.8a)$$

$$\Gamma_1 = \{\alpha \in \Gamma : \epsilon(\alpha, \alpha) = -1\}. \quad \dots(2.8b)$$

Let

$$L_0 = \bigoplus_{\alpha \in \Gamma_0} L_\alpha \quad \dots(2.9a)$$

and

$$L_1 = \bigoplus_{\alpha \in \Gamma_1} L_\alpha. \quad \dots(2.9b)$$

Then we have,

Proposition 1

$$\langle L_0, L_0 \rangle \subset L_0, \langle L_0, L_1 \rangle \subset L_1, \langle L_1, L_1 \rangle \subset L_0. \quad \dots(2.10)$$

PROOF : Let $\alpha, \beta \in \Gamma$. Then

$$\langle L_\alpha, L_\beta \rangle \subset L_{\alpha+\beta} \text{ for all } L_\alpha, L_\beta \in L.$$

It is easy to show that

$$\epsilon(\alpha + \beta, \alpha + \beta) = \epsilon(\alpha, \alpha) \epsilon(\beta, \beta) \quad \dots(2.11)$$

from which (2.11) follows trivially.

The ϵ Jacobi identity may be cast in the following form :

$$\langle A, \langle B, C \rangle \rangle = \langle \langle A, B \rangle, C \rangle + \epsilon(\alpha, \beta) \langle B, \langle A, C \rangle \rangle \quad \dots(2.12)$$

where

$$A \in L_\alpha, B \in L_\beta.$$

(2.10) and (2.12) give L a Γ GLA, the structure of a GLA with commutation factor $\epsilon(\alpha, \beta)$ instead of the usual $(-1)^{\alpha\beta}$. The results in Ref. 8 are now directly applicable and will be used in the next sub-section.

(C) Invariant Forms

Following Mitra and Tripathy¹⁰, we construct invariant forms for L as follows. Let P_0 and P_1 be the orthogonal projections of L onto L_0 and L_1 . We define the multilinear map

$$K_n : L \underset{n \text{ times}}{\otimes} L \dots \otimes L \rightarrow \mathcal{F}, \text{ a scalar field by}$$

$$K_n(l_1, l_2, \dots, l_n) = \text{tr} [P_0 (\text{ad } l_1 \text{ ad } l_2, \dots, \text{ad } l_n) - P_1 (\text{ad } l_1 \text{ ad } l_2, \dots, \text{ad } l_n)] \quad \dots(2.13)$$

for all $l_i \in L, i = 1, 2, \dots, n$, $\text{ad } l$ being the adjoint action of l_i on $l \in L$. It is easily seen using structure constants that $K_n(l_1, l_2, \dots, l_n) = 0$ unless $\sum_{i=1}^n |l_i| = 0$, $\dots(2.14)$

$|l_i| \in \Gamma$ being the degree of homogeneity of $l_i \in L_0 \cup L_1$.

The following lemma is useful.

$$\text{Lemma 1—(a) (i) If } l \in L_0, P_i \text{ ad } l = P_i \text{ ad } l P_i = \text{ad } l P_i \quad \dots(2.15a)$$

$$(ii) \text{ If } l \in L_1, P_i \text{ ad } l = P_i \text{ ad } l P_j = \text{ad } l P_j$$

$$i \neq j = 0, 1 \quad \dots(2.15b)$$

$$(b) \text{ ad } \langle l, m \rangle = \text{ad } l \text{ ad } m - \epsilon(|l|, |m|) \text{ ad } m \text{ ad } l, \quad \dots(2.16)$$

PROOF : (a) The results (i) and (ii) are a direct consequence of (2.2) in Proposition 1 and the fact that P_0 (P_1) annihilate L_1 (L_0) respectively.

(b) This follows from eqn. (2.12).

We now establish the symmetry and invariance properties of K_n .

$$\text{Theorem 1 (a) } K_n(l_1, l_2, \dots, l_n) = \epsilon(|l_1|, |l_l|) K_n(l_2, \dots, l_n, l_l) \quad \dots(2.17)$$

(b) $K_n(l_1, l_2, \dots, l_n) = 0$ if the set $\{l_1, l_2, \dots, l_n\}$ contains an odd no. of elements from L_1 .

$$\begin{aligned} \text{(c) } K_n(\langle l, l_1 \rangle, l_2, \dots, l_n) &+ \sum_{i=2}^n \epsilon(|l|, \sum_{t=1}^{i-1} |l_t|) K_n(l_1, \dots, \langle l, l_i \rangle \\ &\dots, l_n) = 0. \end{aligned} \quad \dots(2.18)$$

PROOF : Using Lemma (1a)

$$\begin{aligned} \text{tr}[P_l \text{ad} l_1 \text{ad} l_2, \dots, \text{ad} l_n] &= \text{tr}(P_l (\text{ad} l_1) (\text{ad} l_2, \dots, \text{ad} l_n)) \\ &= \text{tr}[\text{ad} l_1 P_k (\text{ad} l_2, \dots, \text{ad} l_n)] \\ &= \text{tr}[P_k (\text{ad} l_2, \dots, \text{ad} l_n \text{ad} l_1)], \end{aligned}$$

where

$$\begin{aligned} k &= i \quad \text{if } l_l \in L_0, \\ k &\neq i \quad \text{if } l_l \in L_1. \end{aligned}$$

(using the symmetry of the trace operation).

Hence

$$\begin{aligned} K_n(l_1, l_2, \dots, l_n) &= \text{tr}[P_0(\text{ad} l_1, \dots, \text{ad} l_n) - P_1(\text{ad} l_1 \dots \text{ad} l_n)] \\ &= (-1)^{|l_l|} K_n(l_2, \dots, l_n, l_l) \text{ if } l_l \in L \text{ and } |l_l| = 0, 1 \\ &= \epsilon(|l_1|, |l_l|) K_n(l_2, \dots, l_n, l_l) \\ \text{(b) } K_n(l_1, l_2, \dots, l_n) &= \epsilon(|l_1|, |l_l|) K_n(l_2, \dots, l_n, l_l) \\ &= \prod_{i=1}^n \epsilon(|l_i|, |l_l|) K_n(l_1, l_2, \dots, l_n). \end{aligned} \quad \dots(2.19)$$

From (2.19), $K_n(l_1, l_2, \dots, l_n) = 0$ if there are an odd no. of elements in the set $\{l_1, l_2, \dots, l_n\}$ belonging to L_1 .

(c) Using Lemma(1b) and the properties of $\epsilon(\alpha, \beta)$ we have

$$\epsilon(|l|, \sum_{t=1}^{l-1} |l_t|) K_n(l_1, \dots, \langle l, l_l \rangle, l_{l+1}, \dots, l_n)$$

$$\begin{aligned}
& + \epsilon(|I|, \sum_{i=1}^l |l_i|) K_n(l_1, \dots, l_i < l, l_{i+1} >, \dots, l_n) \\
& = \epsilon(|I|, \sum_{i=1}^{l-1} |l_i|) [K_{n+1}(l_1, \dots, l, l_i, \dots, l_n) \\
& \quad - \epsilon(|I|, |l_i|) K_{n+1}(l_1, \dots, l_i, l, l_{i+1}, \dots, l_n) \\
& \quad + \epsilon(|I|, l_i) K_{n+1}(l_1, \dots, l_i, l, l_{i+1}, \dots, l_n) \\
& \quad - \epsilon(|I|, |l_i| + |l_{i+1}|) K_{n+1}(l_1, \dots, l, l_i l_{i+1}, \dots, l_n)] \\
& = \epsilon(|I|, \sum_{i=1}^{l-1} |l_i|) [K_{n+1}(l_1, \dots, l, l_i, l_{i+1}, \dots, l_n) \\
& \quad - \epsilon(|I|, \sum_{i=1}^{l-1} |l_i|) K_{n+1}(l_1, \dots, l_i, l_{i+1}, l_1, \dots, l_n)] \dots (2.20)
\end{aligned}$$

Using (2.20) we find that the terms in the sum in (2.19) cancel diagonally and the L. H. S. of (2.18) is

$$\begin{aligned}
K_{n+1}(l, l_1, \dots, l_n) &= \epsilon(|I|, \sum_{i=1}^n |l_i|) K_{n+1}(l_1, \dots, l_n, l) \\
&= K_{n+1}(l, l_1, \dots, l_n) [l - \epsilon(|I|, |I| + \sum_{i=1}^n |l_i|)] \dots (2.21)
\end{aligned}$$

(using (2.17)).

From (2.14), using $\epsilon(|I|, 0) = 1$, it is seen that (2.21) is identically zero, proving (2.18).

Thus far, we have established the existence of invariant forms of arbitrary degree (unless some of them vanish identically for a Γ GLA). In particular, there exists a bilinear form K_2 which we call the Cartan-Killing form K defined by

$$K(l, m) = K_2(l, m). \dots (2.22)$$

The symmetry properties of K are listed below :

$$(1) \quad K(l, m) = K(m, l) \text{ for all } l, m \in L_0 \dots (2.23a)$$

$$(2) \quad K(l, m) = 0 \text{ for all } l \in L_0, m \in L_1 \dots (2.23b)$$

$$(3) \quad K(l, m) = -K(m, l) \text{ for all } l, m \in L_1 \dots (2.23c)$$

$K(l, m)$ evidently combines a Riemannian with a symplectic structure being the direct sum of a symmetric form on L_0 and a skew symmetric form on L_1 .

3. CASIMIR INVARIANTS AND STRUCTURE OF A SEMISIMPLE Γ GLA

We isolate the class of Γ GLA for which $\det K(l, m) \neq 0$. These we call nondegenerate following Backhouse¹¹ and Pais and Rittenberg¹².

We now construct Casimir invariants for such Γ GLA. We choose a basis $\{l^\alpha\}$ for L . The dual basis $\{l_\alpha\}$ is chosen by the condition

$$K(l^\alpha, l_\beta) = \delta^\alpha_\beta, \quad \alpha, \beta = 1, \dots, t. \quad \dots(3.1)$$

This is possible as K is nondegenerate. We now show that

$$C_n = K_n(l_{\alpha_1}, \dots, l_{\alpha_n}) l^{\alpha_n}, \dots, l^{\alpha_1} \quad \dots(3.2)$$

is invariant under L . We will need the following lemma.

Lemma 2—(a) If $\langle l, l^\alpha \rangle = L^\alpha_\beta l^\beta$ and $\langle l, l_\beta \rangle = M^\alpha_\beta l_\alpha$

$$M^\alpha_\beta = -\epsilon(|l^\alpha|, |l|) L^{\alpha\beta}. \quad \dots(3.3a)$$

$$(b) \quad |l^\alpha| = -|l_\alpha|. \quad \dots(3.3b)$$

PROOF : (a) $K(l^\alpha, \langle l, l_\beta \rangle) = K(l^\alpha, M^\gamma_\beta l_\gamma) = M^\alpha_\beta$

$$K(\langle l, l^\alpha \rangle, l_\beta) = K(L^\alpha_\gamma l^\gamma, l_\beta) = L^\alpha_\beta.$$

Using Theorem 1c for $n = 2$, the result follows.

$$(b) \quad K(l^\alpha, l_\beta) = \delta^\alpha_\beta = 0 \text{ unless } |l^\alpha| = -|l_\beta|.$$

Hence $\epsilon(|l^\alpha| + |l_\alpha|, |l|) = 1$, so that

$$(i) \quad \epsilon(|l^\alpha|, |l|) = \epsilon(|l|, |l_\alpha|) \quad \dots(3.4a)$$

$$(ii) \quad \epsilon(|l|, |l^\alpha|) = \epsilon(|l_\alpha|, |l|). \quad \dots(3.4b)$$

Invariance of the Casimir operator C under L means that $\text{adl } C = 0$ for all $l \in L$ and $C \in U(L)$, the Universal Enveloping Algebra which consists of linear combinations of monomials of L . The bracket operation adl is defined by

$$\text{adl}(mn) = \langle l, mn \rangle = \langle l, m \rangle n - \epsilon(|l|, |m|) m \langle l, n \rangle.$$

Theorem 2— $C_n = K_n(l_{\alpha_1}, \dots, l_{\alpha_n}) l^{\alpha_n}, \dots, l^{\alpha_1}$ is invariant under L , where $|l|$, $|l_{\alpha_i}|$, $|l^{\alpha_i}|$ are the degrees of l , l_{α_i} , and l^{α_i} respectively, $i = 1, \dots, n$.

PROOF : $\text{adl } C_n = K_n(l_{\alpha_1}, \dots, l_{\alpha_n}) \langle l, l^{\alpha_n} \rangle l^{\alpha_{n-1}}, \dots, l^{\alpha_1}$

$$\begin{aligned}
& + \sum_{i=2}^n \epsilon(|l|, \sum_{k=1}^{l-1} (l_{\alpha_{n-k+1}} |)) K_n(l_{\alpha_1}, \dots, l_{\alpha_{n-i}}, \dots, l_{\alpha_i}) l_{\alpha_n} \\
& \quad \dots < l, l_{\alpha_{n-i+1}} > \dots, l_{\alpha_1} \\
& = K_n(l_{\alpha_1}, \dots, l_{\alpha_n}) L_{\gamma_n}^{\alpha_n} l_{\gamma_n}^{\alpha_{n-1}} \dots l_{\alpha_1} + \sum_{i=2}^n \epsilon(|l|, \sum_{k=1}^{l-1} |l_{\alpha_{n-k+1}}|) \\
& \quad \times K_n(l_{\alpha_1}, \dots, l_{\alpha_{n-i+1}}, \dots, l_{\alpha_n}) \times l_{\alpha_n} \dots L_{\gamma_{n-i+1}}^{\alpha_{n-i+1}} l_{\gamma_{n-i+1}} \dots l_{\alpha_1} \\
& \quad (= l_{\alpha_{n-i+1}}) \dots (3.5)
\end{aligned}$$

Using Lemma 2a, noting that

$$|l_{\gamma_{n-i+1}}| \parallel |l_{\alpha_{n-i+2}}| + |l|, \dots (3.6)$$

and relabelling $l_{\gamma_{n-i+1}}$ as $l_{\alpha_{n-i+1}}$, (3.5) becomes

$$\begin{aligned}
\text{adl } C_n = - [\sum_{i=1}^n \epsilon(|l|, \sum_{k=1}^l |l_{\alpha_{n-k+1}}|) \epsilon(|l|, |l|) K_n(l_{\alpha_1}, \dots, \\
< l, l_{\alpha_{n-i+1}} > \dots l_{\alpha_n})] \times l_{\alpha_n} \dots l_{\alpha_1}. \dots (3.7)
\end{aligned}$$

Using (3.4) and extracting $-\epsilon(\sum_{k=1}^n |l_{\alpha_n}|, |l|) \epsilon(|l|, |l|)$

in (3.7) gives

$$\begin{aligned}
& [K_n(< l, l_{\alpha_1} > \dots l_{\alpha_1}) + \sum_{i=2}^n \epsilon(|l|, \sum_{k=1}^{l-1} |l_{\alpha_k}|) \\
& \quad \times K_n(l_{\alpha_1} \dots < l, l_{\alpha_i} > \dots, l_{\alpha_n})] l_{\alpha_n}, \dots, l_{\alpha_1}
\end{aligned}$$

which is zero by Theorem 1c. This proves the result.

We now make a few remarks on the structure of a nondegenerate Γ GLA which will be used in the next section.

Definition 1—A linear subset N of a Γ GLA L is a left ideal if

$$< L, N > \subset N. \dots (3.8a)$$

A linear subset N of a Γ GLA L is a right ideal if

$$< N, L > \subset N. \dots (3.8b)$$

An ideal N is Abelian if $< N, N > = 0$.

An ideal N of L is a Γ graded ideal if

$$N = \bigoplus_{\gamma \in \Gamma} N_{\gamma} \dots (3.9)$$

Definition 2—The left (right) kernel of a Γ GLA L is the set

$$T_l = \{t \in L, K(t, l) = 0 \text{ for all } l \in L\} \quad \dots(3.10a)$$

$$T_r = \{t \in L, K(l, t) = 0 \text{ for all } l \in L\}. \quad \dots(3.10b)$$

For semisimple Γ GLA, the kernels are obviously trivial.

Definition 3—The left (right) orthogonal complement of a subset N of a Γ GLA L denoted by N_l^\perp (N_r^\perp) is defined as follows

$$N_l^\perp = \{l \in L : K(l, n) = 0 \text{ for all } n \in N\} \quad \dots(3.11a)$$

$$N_r^\perp = \{l \in L : K(n, l) = 0 \text{ for all } n \in N\}. \quad \dots(3.11b)$$

The following lemmas are useful.

Lemma 3—Given $N \subset L$, we define

$$N' = \{n_0 - n_1, \text{ for all } n_0 + n_1 \in N, \text{ where } n_0 \in L_0, n_1 \in L_1\}.$$

Then

$$(N_r')^\perp = (N_l)^\perp.$$

PROOF : Let $l \in (N_r')^\perp$ and $l = l_0 + l_1, l_0 \in L_0, l_1 \in L_1$.

Hence $K(n_0 - n_1, l_0 + l_1) = 0$. By (2.15), $K(l_0 + l_1, n_0 + n_1) = 0$,

that $l \in (N_l)^\perp$. Hence $(N_r')^\perp \subseteq (N_l)^\perp$. The reverse inclusion also holds, hence the result.

When a subset N is Γ graded, $N' = N$. Hence for Γ graded ideals, we may define a unique orthogonal complement which is equal to both the left and right orthogonal complements. We finally have :

Lemma 4— N^\perp , the orthogonal complement of a Γ graded ideal N of a nondegenerate Γ GLA L is a Γ graded ideal.

PROOF : We first show that N^\perp is an ideal of L . By Theorem 1c we may write

$$K(\langle l, n^\perp \rangle, n) + \epsilon(|l|, |n^\perp|) K(n^\perp, \langle l, n \rangle) = 0 \text{ for all } n \in N, n^\perp \in N^\perp, l \in L.$$

The second term vanishes as $\langle l, n \rangle \in N$ is orthogonal to N^\perp . Hence $\langle l, n^\perp \rangle$ is orthogonal to N for all $n^\perp \in N^\perp$, yielding $\langle l, n^\perp \rangle \in N^\perp_l$ for all $l \in L$, and so N^\perp is an ideal of L . We now show that N^\perp is Γ graded.

Let $n^\perp = \sum_{\alpha \in \Gamma} n_\alpha^\perp$ where $n_\alpha^\perp \in N_\alpha^\perp$.

Then as N is Γ graded, if $n = n_\gamma \in N_\gamma$, $K(n^\perp, n) = 0 \Rightarrow$

$$K\left(\sum_{\alpha \in \Gamma} n_\alpha^\perp, n_\gamma\right) = 0.$$

But $K(n_\alpha^\perp, n_\gamma) = 0$ for all $\alpha \neq -\gamma$ by (2.14), so $\exists \gamma' = -\gamma : n_{\gamma'}^\perp \in N_{\gamma'}^\perp$ and $K(n_{\gamma'}^\perp, n_\gamma) = 0$. Also $K(n_{\gamma'}^\perp, n) = 0$ where $n = \bigoplus_{\beta \in \Gamma} n_\beta$ because $K(n_{\gamma'}^\perp, n_\beta) = 0$ for all $\beta \neq -\gamma'$. The above argument holds for all $\gamma \in \Gamma : N = \bigoplus_{\gamma \in \Gamma} N_\gamma$, hence $N^\perp = \bigoplus_{\gamma \in \Gamma} N_\gamma^\perp$. This completes the proof.

Lemma 4 is invaluable in generalising the results of nondegenerate GLA in Ref. 8 to nondegenerate Γ GLA. The results are collected in the following theorem :

Theorem 3—Given a nondegenerate Γ GLA L as defined above. Then,

- (1) There are no nontrivial Γ graded Abelian ideals.
- (2) L may be written as a direct sum of Γ graded ideals $\bigoplus M_\alpha$ where each M_α is nondegenerate¹⁴ and has no nontrivial Γ graded ideal.
- (3) $\langle L, L \rangle = L$(3.12)

The proofs follow on the same lines as in Mitra and Tripathy¹⁰ and are left as an exercise. We now obtain the last result of this section on the structure of nondegenerate Γ GLA's.

Definition 4—Given a Γ GLA L over a Γ graded vector space V . For any $\delta \in \Gamma$, let $D(L, \epsilon)_\delta$ denote the subspace of all elements $D \in gl(V, \epsilon)_\delta$, the general linear \in Lie Algebra of v^{15} :

$$D(\langle a, b \rangle) = \langle D(a), b \rangle + \epsilon(\delta, \alpha) \langle a, Db \rangle$$

\forall elements $a, b \in L$ with degrees $\alpha, \beta \in \Gamma$ respectively, It is easy to see that $D(L, \epsilon) = \bigoplus_{\delta \in \Gamma} D(L, \epsilon)_\delta$ is a Γ graded subalgebra of $gl(L, \epsilon)$. The elements of $D(L, \epsilon)_\delta$ are called the ϵ derivations of degree δ .

Two Γ graded derivations d, d' of degrees $\delta, \delta' \in \Gamma$ respectively combine by the usual bracket $\langle \rangle$ and

$$\langle d, d' \rangle = dd' - \epsilon(\delta, \delta') d'd \text{ for all } d, d' \in D. \quad \dots(3.14)$$

We finally have the following theorem.

Theorem 4—All ϵ derivations of the nondegenerate Γ GLA L are inner i. e.

$$D = \text{ad}L. \quad \dots(3.15)$$

PROOF : We first see that $\text{ad}L$ is a Γ graded ideal of D . We note that for all $l, m \in L$,

$$\langle D, \text{ad}l \rangle m = D \langle l, m \rangle - \in (\delta, |l|) \langle 1, Dm \rangle = \langle Dl, m \rangle \quad \dots(3.16)$$

(using (3.13) and (3.14)).

Now $l \rightarrow \text{ad}l$ is a Γ graded homomorphism of L into D with kernel, the center of L which is trivial as L is non-degenerate. Hence $\text{ad}L$ is a representation of L in D so that $\text{ad}L$ has a nondegenerate Killing form K which is also the restriction of the Killing form K' of D to $\text{ad}L$ as $\text{ad}L$ is an ideal of D ¹⁵.

If $\text{ad}L^\perp$ be the orthogonal complement of $\text{ad}L$ with respect to K' , then the non-degeneracy of K ensure that $\text{ad}L \cap \text{ad}L^\perp$ is zero. It also means that $N = \langle \text{ad}L, \text{ad}L^\perp \rangle = 0$ for both $\text{ad}L$ and $\text{ad}L^\perp$ are Γ graded ideals and N is contained in both $\text{ad}L$ and $\text{ad}L^\perp$. If $d \in \text{ad}L^\perp$, then $0 = \langle d, \text{ad}l \rangle = \text{ad}dl$ for all $l \in L$ from which $dl = 0$ for all $l \in L$, hence $d = 0$. Thus $\text{ad}L^\perp = 0$ which immediately implies that $\text{ad}L = D$.

4. COHOMOLOGY OF NONDEGENERATE Γ GLA :

In this section, we generalize the definition of coboundary operator¹⁰ by considering mappings $f: g \otimes g \dots \otimes g \rightarrow V$ of arbitrary degree ρ , $\rho \in \Gamma$, V is a ϕ module of g and $f(X_1, \dots, X_l, X_{l+1} \dots X_n) = - \in (|X_l|, |X_{l+1}|) f(X_1, \dots, (X_{l+1}, X_l), \dots, X_n)$ for all $X_1, \dots, X_n \in g$... (4.1)

$|X_l|$ being the degree of $X_l \in g$.

In subsequent discussions, we suppress the subscript ρ in f . Our generalized coboundary operator takes the form

$$\begin{aligned} \delta^n f(X_1, \dots, X_{n+1}) &= \sum_{i=1}^{n+1} (-1)^{i+1} \epsilon(|f|, |X_i|) \epsilon\left(\sum_{k=1}^{i-1} |X_k|, |X_i|\right) \\ &\times \phi(X_i) f(X_1, \dots, \hat{X}_i, \dots, X_{n+1}) + \sum_{i < j=1} (-1)^{i+j} \epsilon\left(\sum_{k=1}^{i-1} |X_k|, |X_i|\right) \\ &\times \epsilon\left(\sum_{l=1}^{j-1} |X_l|, |X_j|\right) \epsilon(|X_j|, |X_i|) f(\langle X_i, X_j \rangle, \dots, \hat{X}_i, \dots, \\ &\times \hat{X}_j, \dots, X_{n+1}) \end{aligned} \quad \dots(4.2)$$

The notation $\epsilon\left(\sum_{k=1}^{i-1} |X_k|, |X_i|\right)$ will be shortened to $\epsilon(-i')$

for all elements $X_k \in g$ to which special attention is not being drawn in the text. $\epsilon(|X_j|, |X_i|)$ will be written as $\epsilon(j', i')$. \hat{X}_i , means that X_i is to be omitted in $f(X_1, \dots, X_n)$

The analysis made in the earlier sections allows us to compute the cohomology of a wide class of finite dimensional representations of nondegenerate Γ GLA's. Our results are stated in the following generalisation of Whitehead's lemmas

Theorem 5—Given a nondegenerate Γ GLA \mathfrak{g} over a commutative field \mathcal{F} of characteristic zero, and $\phi: \mathfrak{g} \rightarrow \text{End } V$. Let V be a finite dimensional module of \mathfrak{g}

(1) If $\phi(C_2)$ is invertible, $H^n_{\phi}(\mathfrak{g}, V) = 0$, for all $n > 0$;

(2) If $\phi(X) v_{\beta} = 0$ for all $X \in \mathfrak{g}$, $v_{\beta} \in V_{\beta}$, $\beta \in \Gamma$, then $H^1_{\phi}(\mathfrak{g}, V) = 0$.

PROOF : We introduce the notation

$$|X_i| = i', \quad |l^{\alpha}| = \alpha_1, \quad |l_{\alpha}| = \alpha_2.$$

If $f \in Z^n_{\phi}(\mathfrak{g}, V)$, then

$$\delta^n f(X_1, \dots, X_{n+1}) = 0 \text{ for all } X_1, \dots, X_{n+1} \in \mathfrak{g}.$$

(1) $\phi(C_2)$ is invertible. Let $X_1 = l^{\alpha}$, l^{α} being a member of the dual basis [see eq. (3.1)] of \mathfrak{g} . Then (4.3) implies (not including $|l^{\alpha}|$ in $\epsilon(-l)$ of \mathfrak{g}).

$$\begin{aligned} & \epsilon(|f|, \alpha_1) \phi(l^{\alpha}) f(X_1, \dots, X_n) \\ & + \sum_{i=1}^n (-1)^i \epsilon(|f|, i') \epsilon(\alpha_1, i') \epsilon(-i') \phi(X_i) \\ & \times f(l^{\alpha}, \dots, \hat{X}_i, \dots, X_n) \\ & + \sum_{i=1}^n (-1)^i \epsilon(-i') f(\langle l^{\alpha}, X_i \rangle, \dots, \hat{X}_i, \dots, X_n) \\ & + \sum_{i < j=1}^n (-1)^{i+j} \epsilon(-l') \epsilon(-l') \epsilon(j', i') \epsilon(\alpha_1, i+j') \\ & \times f(\langle X_i, X_j \rangle, l^{\alpha}, \dots, \hat{X}_i, \dots, \hat{X}_j, \dots, X_n) = 0. \end{aligned} \quad \dots(4.4)$$

We operate with $\Sigma \in (|f|, \alpha_2) K(l_{\alpha}, l_{\beta}) \phi(l^{\beta})$ and obtain, dropping summation symbols α, β over the dummy indices α, β , using (3.3b) and simplifying

$$\begin{aligned} & K(l_{\alpha}, l_{\beta}) \phi(l^{\beta}) (l^{\alpha}) f(X_1, \dots, X_n) \\ & + \sum_{i=1}^n (-1)^i \epsilon(-i') \epsilon(|f|, i') \epsilon(|f|, \alpha_2) K(l_{\alpha}, l_{\beta}) \\ & \times \phi(X_i) \phi(l^{\beta}) f(l^{\alpha}, \dots, \hat{X}_i, \dots, X_n) \end{aligned}$$

$$\begin{aligned}
& + \sum_{i=1}^n (-1)^i \epsilon(-i') \epsilon(|f|, i') \epsilon(\alpha_1, i') \epsilon(|f|, \alpha_2) \\
& \quad \times K(l_\alpha, l_\beta) \langle \phi(l^\beta) \phi(X_i) \rangle f(l^\alpha, \dots, \hat{X}_i, \dots, X_n) \\
& + \sum_{i=1}^n (-1)^i \epsilon(-l') \epsilon(|f|, \alpha_2) K(l_\alpha, l_\beta) \phi(l^\beta) f(\langle l^\alpha, X_i \rangle, \dots, \\
& \quad \times \hat{X}_i \dots X_n) \\
& + \sum_{i < j=1}^n (-1)^{i+j+1} \epsilon(-i') \epsilon(-j') \epsilon(j', i') \epsilon(|f|, \alpha_2) \\
& \quad \times K(l_\alpha, l_\beta) \phi(l^\beta) f(l^\alpha, \langle X_i, X_j \rangle, \dots, \hat{X}_i, \dots, \hat{X}_j \dots X_{n+1}) \\
& \quad = 0. \quad \dots(4.5)
\end{aligned}$$

The third and fourth terms may be written as

$$\begin{aligned}
& \sum_{i=1}^n (-1)^{i+1} \epsilon(-i') \epsilon(|f|, \alpha_2) \epsilon(+f|, i') K(l_\alpha, l_\beta) \langle \phi(X_i), \\
& \quad \times \phi(l^\beta) \rangle f(l^\alpha, \dots, \hat{X}_i \dots X_n) \\
& + \sum_{i=1}^n (-1)^{i+1} \epsilon(-i') \epsilon(|f|, \alpha_2) \epsilon(\alpha_1, i') K(l_\sigma, l_\beta) \phi(l^\beta) \\
& \quad \times f(\langle X_i, l^\alpha \rangle, \dots, \hat{X}_i, \dots, X_n) \\
& = \sum_{i=1}^n (-1)^{i+1} \epsilon(-i') \epsilon(|f|, i') \epsilon(|f|, \alpha_2) K(l_\alpha, l_\beta) L_{i\rho}^\beta \phi(l^\rho) f(l^\alpha, \dots, \hat{X}_i \dots X_n) \\
& \quad + \sum_{i=1}^n (-1)^{i+1} \epsilon(-i') \epsilon(|f|, \alpha_2) \epsilon(\alpha_1, i') K(l_\alpha, l_\beta) \phi(l^\beta) \\
& \quad \times L_{i\gamma}^\alpha f(l^\gamma, \dots, \hat{X}_i, \dots, X_n) \quad \dots(4.6)
\end{aligned}$$

where,

$$\langle X_i, l^\beta \rangle = L_{i\rho}^\beta l^\rho \quad \dots(4.7a)$$

$$\langle X_i, l_\beta \rangle = M_{i\beta}^\rho l_\rho. \quad \dots(4.7b)$$

Using (3.3a) and noting that $\alpha_2 = \gamma_2 + i'$, $\beta_2 = \rho_2 + i'$,

we get

$$\sum_{i=1}^n (-1)^i \epsilon(-i') \epsilon(|f|, i' + \alpha_2) \epsilon(\rho_2 + i', i') K(l_\alpha, \langle X_i, l_\beta \rangle)$$

$$\phi(l^\beta) f(l^\alpha, \dots, \hat{X}_i \dots X_n)$$

$$+ \sum_{i=1}^n (-1)^j \epsilon(-i') K(\langle X_i, l_\gamma \rangle, l_\beta) \epsilon(|f|, \gamma_2 + i') \phi(l_\beta) f(l^\gamma,$$

$$\times \dots, \hat{X}_i \dots, X_n).$$

Substituting $\alpha_2 \rightarrow \gamma_2$, $\rho_2 \rightarrow \beta_2$ in the first term and noting that $\gamma_2 = -(\beta_2 + i')$, we get

$$\sum_{i=1}^n (-1)^i \epsilon(-i') \epsilon(|f|, \gamma_2 + i') [K(\langle X_i, l_\gamma \rangle, l_\beta) + \epsilon(i', \gamma_2) K(l_\gamma,$$

$$\langle X_i, l_\beta \rangle)] \phi(l^\beta) f(l^\alpha, \dots, \hat{X}_i \dots X_n) = \dots(4.8)$$

which is zero by Theorem (lc).

Putting $\phi(C_2) = K(l_\alpha, l_\beta) \phi(l^\beta) \phi(l^\alpha)$, (4.5) reduces to

$$f(X_1, \dots, X_n) = \sum_{i=1}^n (-1)^{i+1} \epsilon(-i') \epsilon(|f|, i') \phi(X_i) [\epsilon(|f|, \alpha_2)$$

$$\times K(l_\alpha, l_\beta) \phi(C_2^{-1}) \phi(l^\beta) f(l^\alpha, \hat{X}_i, X_n)]$$

$$+ \sum_{i < j=1}^n (-1)^{i+j} \epsilon(j', i', i') \epsilon(-i') \epsilon(-j') [\epsilon(|f|, \alpha_2)$$

$$K(l_\alpha, l_\beta) \phi(C_2^{-1}) \phi(l^\beta) f(l^\beta) f(l^\alpha, \langle X_i, X_j \rangle \dots \hat{X}_i, \dots, \hat{X}_j, \dots X_n)].$$

...(4.9)

$$\text{Identifying } w(X_1, \dots, X_i, \dots, X_n) = \epsilon(|f|, \alpha_2) K(l_\alpha, l_\beta) \phi(C_2^{-1}) \phi(l^\beta) f(l^\alpha \dots \hat{X}_i \dots X_n).$$

...(4.10)

We find that for any $f(X_1, \dots, X_n)$ there exists a linear mapping $w: g \otimes \dots \otimes g \rightarrow V: f = \delta^{n-1} w$; for all $n > 0$, $(n-1)$ times

when $\delta^n f = 0$.

This proves the result.

$$(2) \quad \phi(X) v_\beta = 0 \text{ for all } X \quad g = \dots \phi(C_2) v_\beta = 0.$$

To prove $H_\phi^1(g, V) = 0$, we see that

$$\delta^1 f(X_1, X_2) = 0 \Rightarrow f(\langle X_1, X_2 \rangle) = 0 \text{ for all } X_1, X_2 \in \mathfrak{g}. f \in Z_\phi^1(\mathfrak{g}, V).$$

By Theorem 3c,

$$f(X) = 0 = \phi(X) v_\beta \text{ for all } X \in \mathfrak{g}, v_\beta \in V_\beta, \beta \in \Gamma.$$

Hence

$$H_\phi^1(\mathfrak{g}, V) = 0.$$

This completes the proof. The results of our analysis apply to all nondegenerate Γ GLA, e.g. $Z_3 \otimes Z_3$, graded algebras (discussed in Ref. 5) and all Lie superalgebras. In passing, we mention that for the orthosymplectic sequence of semisimple GLA, Whithead's lemmas hold i. e.

$$H_\phi^n(\mathfrak{g}, V) = 0, (n = 1, 2). \quad \dots(4.11)$$

5. APPLICATIONS OF THE COHOMOLOGY

The two major applications of the cohomology that we discuss below are :

(a) Extensions of algebras by Abelian ideals.

(b) Reducibility of representations.

(a) *Extensions of Algebras by Abelian Ideals*—This was discussed in sufficient details in Mitra and Tripathy¹⁰. The only additional remark we wish to make here is that for the class of Γ graded Abelian ideals A which form a representation of semisimple Γ GLA of such that $\phi(C_2)$ is invertible, the extension of \mathfrak{g} by A is trivially accomplished by the semidirect sum.

(b) *Reducibility of Representations*—One of the most fundamental theorems in the theory of semisimple Lie Algebras is the theorem of H. Weyl which asserts that every finite dimensional representation V of the semisimple Lie Algebra \mathfrak{g} is semisimple i. e. has the property that every \mathfrak{g} invariant submodule W of V has a \mathfrak{g} invariant complement \bar{W} , so that it is completely reducible and the study of a representation of a semisimple LA reduces to the study of its irreducible representations. In what follows, we formulate the generalised Weyl's reducibility theorem for nondegenerate Γ GLA drawing freely from Jacobson¹⁶ and Vardarajan¹⁷.

Theorem 6—Let \mathfrak{g} be a Γ GLA over a commutative field \mathcal{F} . Then all finite dimensional ϕ modules V of \mathfrak{g} are semisimple if $H_\sigma^1(\mathfrak{g}, F) = 0$,

where F and σ are defined in eqn. (5.4) and (5.6) respectively.

PROOF : Let W be a Γ graded submodule of V invariant under \mathfrak{g} so that $0 \neq W \neq V$. We select a Γ graded subspace \bar{W} of V complementary to W . If A is any projection of V onto W i. e.

$$A^2 = A \quad \dots(5.1)$$

$$A [w_\beta] = w_\beta \text{ for all } w_\beta \in W_\beta \quad \dots(5.1b)$$

$$A [\bar{w}_\beta] = 0 \text{ for all } \bar{w}_\beta \in \bar{W}_\beta, \beta \in \Gamma. \quad \dots(5.1c)$$

It follows trivially that A is Γ homogeneous of degree zero. We now use the following lemma :

Lemma 5— \bar{W} is invariant under ϕ , if and only if

$$\langle A, \phi(X) \rangle = 0 \text{ for all } X \in \mathfrak{g}. \quad \dots(5.2)$$

PROOF : Let $v_\beta = (w_\beta + \bar{w}_\beta)$ for all $\beta \in \Gamma$.

Then,

$$\begin{aligned} \forall X \in \mathfrak{g}, A\phi(X) v_\beta &= A\phi(X) (w_\beta + \bar{w}_\beta) \\ &= \phi(X) w_\beta + A\phi(X) \bar{w}_\beta \end{aligned}$$

and

$$\phi(X) A v_\beta = \phi(X) w_\beta.$$

Hence

$$\langle A, \phi(X) \rangle v_\beta = A\phi(X) \bar{w}_\beta \quad \dots(5.3)$$

Let $\phi(X) \bar{w}_\beta \in \bar{W}_{|x|+\beta}$, i. e. \bar{w} is invariant under \mathfrak{g} .

Then the right-hand side of (5.3) is zero, implying that

$$\langle A, \phi(X) \rangle = 0 \text{ for all } \beta \in \Gamma, X \in \mathfrak{g}.$$

Conversely, from (5.3) using $\langle A, \phi(X) \rangle = 0$, we find that

$$\phi(X) \bar{w}_\alpha \in \bar{W}_{|x|+\alpha} \text{ for all } \alpha, |X| \in \Gamma, \bar{w}_\alpha \in \bar{W}_\alpha$$

proving the lemma.

All Γ homogeneous projections B of degree zero of V onto W may not satisfy (5.2), so we must modify the equation in order to be able to construct a Γ homogeneous projection of degree zero A' , satisfying the same. To this end, we introduce the vector space F of all endomorphisms of V : $C \in F, C[V] \subseteq W, C[W] = \{0\}$. .. (5.4)

Since $0 \neq W \neq V$, it follows that an endomorphism A' of V is a Γ homogeneous projection of degree zero of V onto W if and only if it is of the form $(B - C)$ for a suitable Γ homogeneous $C \in F$ of degree zero such that

$$\langle \phi(X), B \rangle = \langle \phi(X), C \rangle \text{ for all } X \in \mathfrak{g}. \quad \dots(5.5)$$

It follows from the definition of F that if $D \in F$, then for any endomorphism L of V that leaves W invariant, both LD and DL belong to F . In particular, if we set

$$\sigma(X)D = \langle \phi(X), D \rangle \text{ for all } X \in \mathfrak{g}, D \in F. \quad (5.6)$$

Then $\sigma(X): D \rightarrow \sigma(X)D$ is an endomorphism of F for all $X \in \mathfrak{g}$. We may verify trivially that σ is a representation for

$$\begin{aligned} \langle \sigma(X), \sigma(Y) \rangle D &= \langle \phi(X), \langle \phi(Y), D \rangle \rangle - \epsilon(|X|, |Y|) \\ &\quad \times \langle \phi(Y), \langle \phi(X), D \rangle \rangle \\ &= \langle \langle \phi(X), \phi(Y) \rangle, D \rangle = \langle \phi(\langle X, Y \rangle), D \rangle \\ &= \sigma(\langle X, Y \rangle) D \end{aligned}$$

(by the ϵ Jacobi identity).

On the other hand, it follows from the relations

$$Bw_\beta = w_\beta \text{ for all } w_\beta \in W_\beta, \beta \in \Gamma. \quad \dots(5.7a)$$

$$Bv_\beta \in W_\beta \text{ for all } v_\beta \in V_\beta, \quad \dots(5.7b)$$

that for any $X \in \mathfrak{g}$, $\langle \phi(X), B \rangle$ is an element of F . Let

$$\theta(X) = \langle \phi(X), B \rangle \text{ for all } X \in \mathfrak{g}. \quad \dots(5.8)$$

This θ is a linear map of \mathfrak{g} in F . We now calculate $d\theta$. We have for all $X, Y \in \mathfrak{g}$.

$$\begin{aligned} d\theta(X, Y) &= \langle \phi(X), \langle \theta(Y), B \rangle \rangle - \epsilon(|X|, |Y|) \langle \phi(Y), \\ &\quad \langle \phi(X), B \rangle \rangle - \langle \phi(\langle X, Y \rangle), B \rangle = 0. \end{aligned}$$

Hence

$$\theta \in Z_{\sigma}^1(\mathfrak{g}, F), \text{ If } H_{\sigma}^1(\mathfrak{g}, F) = 0 \quad \dots(5.9)$$

$$\exists D \in F: \theta(X) = \sigma(X)D \text{ for all } X \in \mathfrak{g}. \quad \dots(5.10)$$

D being Γ homogeneous of degree zero as may be seen from (5.7) and (5.8).

Thus $\langle \phi(X), B \rangle = \langle \phi(X), D \rangle$ for all $X \in \mathfrak{g}$. which is just (5.5). Hence the conclusion

We now see that all finite dimensional modules of the $Osp(1|2p)$ sequence are reducible as $H_{\varphi}^1(\mathfrak{g}, V) = 0$ for all finite dimensional modules of the algebra by (4.11).

We thus reproduce part of the results of the Hochschild Djoković Theorem¹⁷. i.e. the $Osp(1|2p)$ sequence is the only sequence of Lie superalgebras for which all finite dimensional modules are completely reducible.

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APPENDIX I

$H_\phi^n(g, V) = 0$ ($n = 1, 2$), for all finite dimensional modules of the orthosymplectic $Osp(1 | 2p)$.

PROOF : For this sequence.

$$\phi(C_2) = - \sum_{\alpha=1}^p v_\alpha (v_\alpha + 2p + 1 - 2\alpha) \quad \dots(A1)$$

v_α being the eigenvalue of H_α for the highest weight vector¹⁹ H_α being an element of the Cartan subalgebra. From Kac²⁰, we see that

$$v_\alpha = 2p, p \in \mathbb{Z}^+.$$

It is easy to see that if

$$\phi(C_2) = 0, v_\alpha = 0 \text{ for all } \alpha = 1, \dots, p$$

hence,

$$\phi(X) v_\beta = 0 \text{ for all } X \in g, v_\beta \in V_\beta, \beta \in \Gamma. \quad \dots(A2)$$

Hence, when Case(1) of Theorem 5 does not apply, Case (2) does, and it follows that $H_\phi^1(\mathfrak{g}, V) = 0$ for all finite dimensional modules V of \mathfrak{g} .

We now show that $H_\phi^2(\mathfrak{g}, V) = 0$, \mathfrak{g} being a member of the orthosymplectic sequence and V a finite dimensional module of \mathfrak{g} .

If $f \in Z_\phi^2(\mathfrak{g}, V)$, then, $f = f_0 + f_1$, (A3) f_0 and f_1 being defined on V_0 and V_1 respectively.

V_0 is the submodule of V on which (A2) holds and

V_1 the submodule of V on which $\phi(C_2)$ is invertible.

Both subspaces are invariant under \mathfrak{g} and have on element in common except 0, also span V , hence $V = V_0 \oplus V_1$. In considering $f_1 : \mathfrak{g} \otimes \mathfrak{g} \rightarrow V_1$, $\phi(C_2)$ is invertible on V_1 and Theorem 5 applies. In considering $f_0 : \mathfrak{g} \otimes \mathfrak{g} \rightarrow V_0$, we see that (A2) applies on V_0 . Then if $f_0 \in Z_\phi^2(\mathfrak{g}, V_0)$,

$$\delta^2 f_0(X_1, X_2, X_3) = 0$$

$$\Rightarrow f_0(\langle X_1, X_2 \rangle, X_3) + \epsilon(|X_1|, |X_2| + |X_3|) f_0(\langle X_2, X_3 \rangle, X_1) - \epsilon(|X_2|, |X_3|) f_0(\langle X_1, X_3 \rangle, X_2) = 0. \quad \dots(A4)$$

Let \mathcal{X} denote the Γ graded vector spaces of linear mappings of \mathfrak{g} into V_0 . We make this into a \mathfrak{g} module by defining for $A \in \mathcal{X}$, $X_1, X_2 \in \mathfrak{g}$.

$$\phi(X_1) A(X_2) = -\epsilon(|X_1|, |A|) A(\langle X_1, X_2 \rangle). \quad \dots(A5)$$

This satisfies the module conditions given in Jacobson¹⁶ (Chapter 1) which admit of the following generalization :

$$(1) [\phi(X_1) + \phi(X_2)] A(X) = \phi(X_1) A(X) + \phi(X_2) A(X)$$

$$(2) \alpha \phi(X_1) A(X) = \phi(\alpha X_1) A(X) = \phi(X_1) A(\alpha X)$$

$$(3) \phi(\langle X_1, X_2 \rangle) A(X) = \phi(X_1) \phi(X_2) A(X) - \epsilon(|X_1|, |X_2|) \phi(X_2) \phi(X_1) A(X)$$

For all $X_1, X_2 \in \mathfrak{g}$, $\alpha \in \mathcal{F}$, a commutative field.

For each $X_i \in \mathfrak{g}$, we define an element $A_{X_i} \in \mathcal{X}$, as the mapping $A_{X_i}(X_1) = f_0(X_i, X_1)$ $\mathfrak{g} \otimes \mathfrak{g} \rightarrow V_0$.

Then $X_i \rightarrow A_{X_i}$ is a linear mapping of \mathfrak{g} into \mathcal{X} and

$$A_{\langle X_2, X_3 \rangle}(X_1) = f_0(\langle X_2, X_3 \rangle, X_1) \quad \dots(A6)$$

$$\begin{aligned}
& -\epsilon(|A|, |X_3|) \epsilon(|X_2|, |X_3|) \phi(X_3) A_{X_2}(X_1) \\
& = f_0(X_2, \langle X_3, X_1 \rangle) \dots (A7)
\end{aligned}$$

$$\begin{aligned}
& \epsilon(|A|, |X_2|) \phi(X_2) A_{X_3}(X_1) = -\epsilon(|X_2|, |X_3|) \\
& \times f_0(X_3, \langle X_2, X_1 \rangle). \dots (A8)
\end{aligned}$$

By (A4-A8), $A_{\langle X_2, X_3 \rangle}(X_1) = \epsilon(|A|, |X_2|) \phi(X_2) A_{X_3}(X_1)$

$$= -\epsilon(|X_2|, |X_3|) \epsilon(|A|, |X_3|) \phi(X_3) A_{X_2}(X_1).$$

Hence,

$$A_{X_1} \in Z_{\phi}^1(\mathfrak{g}, x).$$

As $H_{\phi}^1(\mathfrak{g}, \mathcal{X}) = 0$ for all finite dimensional modules \mathcal{X} of \mathfrak{g} , then there exists

$$\rho : \mathfrak{g} \rightarrow V_0 :$$

$$A_{X_i}(X_1) = \epsilon(|\rho|, |X_i|) \phi(X) \rho(X_1)$$

$$\Rightarrow f(X_i, X_1) = -\rho(\langle X_i, X_1 \rangle)$$

proving the result for V_0 .

Hence $H_{\phi}^1(\mathfrak{g}, V) = H_{\phi}^2(\mathfrak{g}, V) = 0$ for all finite dimensional modules V of the ortho-symplectic sequence $Osp(1 | 2p)$.

(N, p, q) SUMMABILITY OF JACOBI SERIES

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In this paper, the authors prove a theorem on (N, p, q) summability of Jacobi series at the point $x = 1$.

§1. Let $\{p_n\}$ be a sequence such that $p_0 > 0, p_n > 0, n \geq 0, P_n = \sum_{k=0}^n p_k \rightarrow \infty$ as $n \rightarrow \infty$ and

$$\bar{t}_n = P_n^{-1} \sum_{k=0}^n P_k S_k \rightarrow S \text{ when } n \rightarrow \infty$$

then we say that $\{S_n\}$ is summable by Riesz means and we write³

$$S_n \rightarrow S (\bar{N}, p_n) \quad \dots(1.1)$$

where $\{S_n\}$ is the sequence of n th partial sums of the series $\sum_{n=0}^{\infty} a_n$. If

$$t_n = P_n^{-1} \sum_{k=0}^n p_k S_{n-k} \rightarrow S \text{ when } n \rightarrow \infty,$$

then we say that $\{S_n\}$ is summable by Nörlund means and we write³

$$S_n \rightarrow S (N, p_n).$$

Let p denotes the sequence $\{p_n\}$, $p_{-1} = 0$. We use similar notations with other letters in place of p . Given two sequences p and q . the convolution $p * q$ is defined by

$$(p * q)_n = \sum_{k=0}^n p_{n-k} q_k \quad \dots(1.3)$$

It is familiar and can be easily verified, that the operation of convolution is commutative and associative and

$$(p * 1)_n = \sum_{k=0}^n p_k, \text{ where } 1 \text{ denotes the sequence } \{1\}.$$

For any sequence $\{S_n\}$, we write

$$t_n^{p,q} = \frac{1}{(p * q)_n} \sum_{k=0}^n p_{n-k} q_k S_k \quad \dots(1.4)$$

Definition—Generalized Nörlund Summability (N, p, q) —If $(p * q)_n \neq 0$ for all n , then the generalized Nörlund transform $((N, p, q)$ transform) of the sequence $\{S_n\}$ is the sequence $\{t_n^{p,q}\}$. If $t_n^{p,q} \rightarrow S$ as $n \rightarrow \infty$, then the sequence $\{S_n\}$ is said to be summable by generalized Nörlund method (N, p, q) to S and is denoted by¹

$$S_n \rightarrow S (N, p, q). \quad \dots(1.5)$$

Two important particular cases of (N, p, q) means are

- (i) (N, p_n) mean when $q_n = 1$ for all n
- (ii) (\bar{N}, q_n) mean when $p_n = 1$ for all n .

The necessary and sufficient conditions for a (N, p, q) method to be regular are

$$\sum_{k=0}^n |p_{n-k} q_k| = O(|(p * q)_n|)$$

and

$$p_{n-k} = o(|(p * q)_n|),$$

as $n \rightarrow \infty$, for every fixed $k \geq 0$, for which $q_k \neq 0$.

§2. Let $f(x)$ be defined in the closed interval $[-1, 1]$ such that the function $(1-x)^\alpha (1+x)^\beta f(x) \in L[-1, 1]$, $\alpha > -1$, $\beta > -1$. The Jacobi series corresponding to this function is

$$f(x) \sim \sum_{n=0}^{\infty} a_n P_n^{(\alpha, \beta)}(x) \quad \dots(2.1)$$

where

$$a_n = \frac{(2n + \alpha + \beta + 1) \Gamma(n + 1) \Gamma(n + \alpha + \beta + 1)}{2^{\alpha + \beta + 1} \Gamma(n + \alpha + 1) \Gamma(n + \beta + 1)}$$

$$\times \int_{-1}^1 (1-x)^\alpha (1+x)^\beta f(x) P_n^{(\alpha, \beta)}(x) dx \quad \dots(2.2)$$

and $P_n^{(\alpha, \beta)}(x)$ are the well-known Jacobi polynomials.

We write

$$F(\phi) = \{f(\cos \phi) - A\} \left(\sin \frac{\phi}{2}\right)^{2\alpha+1} \left(\cos \frac{\phi}{2}\right)^{2\beta+1}. \quad \dots(2.3)$$

$[\lambda]$ denotes the integral part of λ and $P(1/\phi) = P_{[1/\phi]}$.

§3. Quite a good amount of work in the ordinary Nörlund summability of Jacobi series at the point $x = 1$ has been done during the last decade. None seems to have so far tackled the problem of (N, p, q) summability of Jacobi series at $x = 1$. In this note we attempt to establish a result on (N, p, q) summability of Jacobi series at $x = 1$, in the form of the following theorem.

Theorem—Let $\{p_n\}$ be a non-negative, non-increasing sequence and $\{q_n\}$ be a non-negative, non-decreasing sequence such that

$$\sum_{k=c}^n \frac{P_k}{(\log k) k^{\alpha+3/2}} = O\left(\frac{(p * q)_n}{q_n n^{\alpha+1/2}}\right) \quad \dots(3.1)$$

c is a fixed positive integer,

and

$$q_n P_n = O(\log n) (p * q)_n. \quad \dots(3.2)$$

If

$$F_1(t) = \int_0^t |F(\phi)| d\phi = o(t^{2\alpha+2}/\log(1/t)) \text{ as } t \rightarrow 0 \quad \dots(3.3)$$

then the Jacobi series (2.1) is summable (N, p, q) to the sum A , provided that $-\frac{1}{2} \leq \alpha < \frac{1}{2}$, $-\frac{1}{2} < \beta$ and the antipole condition

$$\int_{-1}^b (1+x)^{(\beta-\alpha-1)/2} |f(x)| dx < \infty \quad \dots(3.4)$$

b fixed, is satisfied.

Note : (i) For $q_n = 1$ for all n , our theorem reduces to the theorem of Gupta² which is as follows :

*Theorem*²—Let $\{p_n\}$ be a non-negative, non-increasing sequence such that

$$\sum_{k=a}^n \frac{P_k}{k^{\alpha+3/2} \log k} = O\left(\frac{P_n}{n^{\alpha+1/2}}\right), \text{ } a \text{ being fixed positive integer} \quad \dots(3.5)$$

$$\sum_{n=1}^{\infty} \frac{n^{\alpha+1/2}}{P_n} < \infty. \quad \dots(3.6)$$

If (3.3) holds good then the series (2.1) is summable (N, p_n) at the point $x = 1$ to the sum A . provided $-\frac{1}{2} \leq \alpha, < \frac{1}{2}, \beta > -\frac{1}{2}$ and the antipole condition

$$\int_{-1}^b (1+x)^{\beta/2-3/4} |f(x)| dx < \infty. \quad \dots(3.7)$$

b fixed, is satisfied.

It is to be noted that we do not assume (3.6). Also (3.4) is a weaker condition than (3.7), (3.2) is automatically satisfied if $q_n = 1$ for all n .

(ii) (a) If $q_n = 1$ for all n , $p_n = A_n^{\alpha+\delta-1/2}$, $\delta > 0$, $\frac{1}{2} \geq \alpha + \delta$

(b) Or, if $p_n = 1$ for all n and sequence $\{q_n\}$ is such that for all sufficiently large n ,

$$Q_n (= \sum_{k=0}^n q_k) = \exp \{(\log n)^2\}, n \neq 0.$$

For smaller n we define $\{q_n\}$ to be a non-negative, non-decreasing sequence, all conditions of the theorem are satisfied.

If we take $\{p_n\}$ and $\{q_n\}$ be two sequences satisfying the conditions of the theorem but which are such that

$$(N, p_n) \Rightarrow (N, p, q) \quad \dots(3.8)$$

then the theorem does not really give us anything since Gupta's theorem shows that the Jacobi series is summable (N, p_n) and by (3.8) this gives us that it is summable (N, p, q) . It is obvious that (3.8) holds in the example (a).

So we would like to show that it is possible for the conditions of our theorem to be satisfied, but (3.8) to be false. We will now prove that (b) is such an example.

Let us write

$$p(z) = \sum_{n=0}^{\infty} p_n z^n, c(z) = \frac{1}{p(z)} = \sum_{n=0}^{\infty} c_n z^n.$$

Let $\{t_n\}$ and u_n denote respectively the (N, p_n) and (N, p, q) transforms of the sequence $\{S_n\}$, Then

$$\begin{aligned} u_n &= \frac{1}{(p * q)_n} \sum_{k=0}^n p_{n-k} q_k S_k \\ &= \frac{1}{(p * q)_n} \sum_{k=0}^n p_{n-k} q_k \sum_{m=0}^k c_{k-m} P_m t_m \\ &= \frac{1}{(p * q)_n} \sum_{m=0}^n P_m t_m \sum_{k=m}^n p_{n-k} c_{k-m} q_k \\ &= \sum_{m=0}^n \alpha_{nm} t_m, \text{ say.} \end{aligned} \quad \dots(3.9)$$

In order that (3.8) should hold, it is necessary and sufficient that the transformation (3.9) should be regular. For this, it is necessary that

$$\sum_{m=0}^n |\alpha_{nm}| = O(1)$$

Or thus, it is necessary that

$$\alpha_{nn} = O(1)$$

in other words that

$$P_n q_n = O((p * q)_n). \quad \dots(3.10)$$

Thus it is enough to obtain an example in which the conditions of the theorem are satisfied but (3.10) is fake. For the purpose we use example (b). In example (b) (3.10) is fake, for we have

$$\begin{aligned} P_n q_n &= n q_n \\ &\neq O(Q_n) \\ &= O((p * q)_n). \end{aligned}$$

Also (3.2) and (3.1) holds good, for

$$\begin{aligned} P_n q_n &= n q_n \\ &= O(\exp(\log n)^2 (\log n)) \\ &= O(Q_n \log n) \\ &= O((p * q)_n \log n) \end{aligned}$$

and

$$\begin{aligned}
 q_n^{\alpha+1/2} \sum_{k=c}^n \frac{P_k}{k^{\alpha+3/2} \log k} &= q_n n^{\alpha+1/2} \sum_{k=c}^n \frac{1}{k^{\alpha+1/2} \log k} \\
 &= O \left(q_n n^{\alpha+1/2} \frac{n^{1/2-\alpha}}{\log n} \right) \\
 &= O \left(\frac{n q_n}{\log n} \right) = O(Q_n) = O((p * q)_n).
 \end{aligned}$$

(iii) An exactly similar theorem may be stated for the point $x = -1$. The usual modifications will have to be made between the parameters α and β .

§4. We require the following lemmas :

*Lemmes 1*⁷ If $\alpha > -1$, $\beta > -1$, then as $n \rightarrow \infty$.

$$P_n^{(\alpha, \beta)}(\cos \theta) = O(n^\alpha), \quad 0 \leq \theta \leq 1/n \quad \dots(4.1)$$

$$= O(n^\beta), \quad \pi - 1/n \leq \theta \leq \pi \quad \dots(4.2)$$

$$\begin{aligned}
 &= n^{-1/2} k(\theta) \left[\cos(N\theta + r) + \frac{O(1)}{n \sin \theta} \right], \\
 &1/n \leq \theta \leq \pi - 1/n. \quad \dots(4.3)
 \end{aligned}$$

where

$$k(\phi) = \pi^{-1/2} \left(\sin \frac{\phi}{2} \right)^{-\alpha-1/2} \left(\cos \frac{\phi}{2} \right)^{-\beta-1/2}$$

$$N = n + \frac{\alpha + \beta + 1}{2}, \quad r = -(\alpha + \frac{1}{2}) \pi/4$$

Lemma 2—The antipole condition (3.4) implies that

$$\int_{\delta}^{\pi} |F(\phi)| \left(\cos \frac{\phi}{2} \right)^{-\alpha-\beta-1} d\phi < \infty, \quad 0 < \delta < \pi. \quad \dots(4.4)$$

PROOF : Following Gupta² (Or putting $x = \cos \phi$ in (3.4)), we can easily establish the lemma.

Lemma 3—The condition (3.1) implies that

$$q_n n^{\alpha+1/2} = o((p * q)_n) \quad \dots(4.5)$$

PROOF : Following Pandey⁵ we can easily establish the lemma.

Lemma 4—If $\{p_n\}$ is a non-negative, non-increasing sequence than for large n , uniformly in $0 < \phi \leq \pi$, $0 \leq a \leq b \leq n$,

$$\left| \sum_{k=a}^n p_k \cos \{(n-k+\rho)\phi - r\} (n-k)^{\alpha+1/2} \right| = O(n^{\alpha+1/2} P(1/\phi)) \quad \dots(4.6)$$

where

$$\rho = \frac{\alpha + \beta + 2}{2}, r = \left(\alpha + \frac{3}{2}\right) \frac{\pi}{2}, \alpha \geq -1/2.$$

Lemma 5— If $\{p_n\}$ is a non-negative, non-increasing sequence and $\{q_n\}$ is a non-negative non-decreasing sequence then

$$\frac{P_n Q_n}{n+1} \leq (p * q)_n \quad \dots(4.7)$$

PROOF : We have

$$(p * q)_n - P_n Q_n / (n+1) = \sum_{k=0}^n q_k (p_{n-k} - P_n / (n+1)).$$

The sum of coefficients of q_k (where $k = 0, 1, 2, \dots$) on the R. H. S. of the above equation is 0. For fixed n , the coefficients are non-decreasing with k . So for a given n , the coefficients must be all ≤ 0 upto a certain point and all positive beyond that point. Let k_0 be the greatest value of k for which the coefficient is ≤ 0 , where k_0 depends on n . If $k \leq k_0$ then

$$p_{n-k} - \frac{P_n}{n+1} \leq 0$$

and

$$q_k \leq q_{k_0} \text{ by definition of } \{q_n\}.$$

Hence

$$q_k \left(p_{n-k} - \frac{P_n}{n+1} \right) \geq q_{k_0} \left(p_{n-k} - \frac{P_n}{n+1} \right).$$

If $k > k_0$, we have

$$p_{n-k} - \frac{P_n}{n+1} > 0.$$

and

$$q_k > q_{k_0}.$$

Hence, once again we have

$$q_k \left(p_{n-k} - \frac{P_n}{n+1} \right) \geq q_{k_0} \left(p_{n-k} - \frac{P_n}{n+1} \right).$$

Therefore

$$\begin{aligned}
 (p * q)_n - \frac{P_n Q_n}{n+1} &= \sum_{k=0}^n q_k \left(p_{n-k} - \frac{P_n}{n+1} \right) \\
 &\geq q_{k_0} \sum_{k=0}^n \left(p_{n-k} - \frac{P_n}{n+1} \right) \\
 &= 0
 \end{aligned}$$

which proves the result.

Lemma 6—Under the hypothesis of theorem

$$\sum_{v=0}^n q_v v^{\alpha-1/2} = O(q_n n^{\alpha-1/2}) \quad \dots(4.8)$$

PROOF : We have

$$Q_n n^{\alpha-1/2} - Q_{n-1} (n-1)^{\alpha-1/2} = q_n n^{\alpha-1/2} - Q_{n-1} \{(n-1)^{\alpha-1/2} - n^{\alpha-1/2}\}.$$

But since $\{q_n\}$ is non-decreasing

$$Q_{n-1} \leq Q_n \leq (n+1) q_n.$$

Also

$$(n-1)^{\alpha-1/2} - n^{\alpha-1/2} \sim \left(\frac{1}{2} - \alpha\right) n^{\alpha-3/2}.$$

Let d be any constant chosen so that $\frac{1}{2} - \alpha < d < 1$, then for sufficiently large n , say for $n \geq n_0$, we have $Q_{n-1} \{(n-1)^{\alpha-1/2} - n^{\alpha-1/2}\} \leq d q_n n^{\alpha-1/2}$. Therefore,

$$Q_n n^{\alpha-1/2} - Q_{n-1} (n-1)^{\alpha-1/2} \geq (1-d) q_n n^{\alpha-1/2}$$

Hence, summing we get

$$\begin{aligned}
 \sum_{v=n_0}^n q_v v^{\alpha-3/2} &\leq \frac{1}{1-d} \{Q_n n^{\alpha-1/2} - Q_{n_0} - 1(n_0-1)^{\alpha-1/2}\} \\
 &\leq \frac{1}{1-d} Q_n n^{\alpha-1/2}. \quad \dots(a)
 \end{aligned}$$

But

$$\sum_{v=1}^{n_0-1} q_v v^{\alpha-1/2} = O(Q_n n^{\alpha-1/2}) \quad \dots(b)$$

since the L. H. S. is a constant and $Q_n n^{\alpha-1/2} \rightarrow \infty$ as $n \rightarrow \infty$, adding (a) and (b) we are done.

Lemma 7—Under the hypothesis of the theorem

$$\sum_{k=0}^{n-1} p_k q_{n-k} (n-k)^{\alpha-1/2} = O((p * q)_n n^{\alpha-1/2}). \quad \dots(4.9)$$

PROOF : Let M denote a constant, possibly different at each occurrence. For $k \leq n/2$.

$$(n-k)^{\alpha-1/2} \leq \left(\frac{1}{2}\right)^{\alpha-1/2} n^{\alpha-1/2} = M n^{\alpha-1/2}.$$

So the contribution to the sum on the left of (4.9) of the range $0 \leq k \leq n/2$ is

$$\leq M n^{\alpha-1/2} \sum_{0 \leq k \leq n/2} p_k q_{n-k}$$

$$\leq M n^{\alpha-1/2} \sum_{k=0}^n p_k q_{n-k}$$

$$= M n^{\alpha-1/2} (p * q)_n.$$

For the part of the sum with $k > n/2$, we have

$$p_k \leq \frac{P_k}{k+1} \leq \frac{P_n}{\frac{1}{2}(n+1)} = M \frac{P_n}{n+1}.$$

Thus the contribution of this part is

$$\leq M \frac{P_n}{n+1} \sum_{n/2 < k \leq n-1} q_{n-k} (n-k)^{\alpha-1/2}.$$

Now let m be the greatest integer with $n-m > n/2$. Then the sum is equal to

$$M \frac{P_n}{n+1} \sum_{v=1}^m q_v v^{\alpha-1/2} \leq M \frac{P_n}{n+1} Q_m [m^{\alpha-1/2} \quad \text{(by Lemma 6)}$$

$$\leq M \frac{P_n Q_n}{n+1} n^{\alpha-1/2}$$

$$\leq M n^{\alpha-1/2} (p * q)_n \quad \text{(by Lemma 5)}$$

which proves the result.

Lemma 8—Let

$$N(\phi) = \frac{2^{\alpha+\beta+1}}{(p * q)_n} \sum_{k=0}^{n-1} p_k q_{n-k} \lambda_{n-k} P_{n-k}^{(\alpha+1, \beta)}(\cos \phi)$$

where

$$\lambda_n = \frac{2^{-\alpha-\beta-1} \Gamma(n+\alpha+\beta+2)}{\Gamma(\alpha+1) \Gamma(n+\beta+1)} \cong \frac{2^{-\alpha-\beta-1}}{\Gamma(\alpha+1)} n^{\alpha+1}$$

then, for $\frac{1}{2} > \alpha \geq -\frac{1}{2}$, $\beta > -\frac{1}{2}$, and if $\{p_n\}, \{q_n\}$ satisfies the hypothesis of the theorem.

$$N(\phi) = O(n^{2\alpha+2}) \text{ if } 0 \leq \phi \leq 1/n \quad \dots(4.10)$$

$$= O(n^{\alpha+\beta+1}) \text{ if } \pi - 1/n \leq \phi \leq \pi \quad \dots(4.11)$$

$$= O \left[\frac{q_n n^{\alpha+1/2} P(1/\phi)}{(p * q)_n} \left(\sin \frac{\phi}{2} \right)^{-\alpha-3/2} \left(\cos \frac{\phi}{2} \right)^{-\beta-1/2} \right] \\ + O \left[n^{\alpha-1/2} \left(\sin \frac{\phi}{2} \right)^{-\alpha-5/2} \left(\cos \frac{\phi}{2} \right)^{-\beta-3/2} \right],$$

$$\frac{1}{n} \leq \phi \leq \pi - 1/n. \quad \dots(4.12)$$

PROOF : For $0 \leq \phi \leq 1/n$, using (4.1) we get

$$N(\phi) = O[(p * q)_n^{-1} \sum_{k=0}^{n-1} p_k q_{n-k} (n-k)^{2\alpha+2}] \\ = O(n^{2\alpha+2})$$

If $\pi - 1/n \leq \phi \leq \pi$, using (4.2) we get (4.11).

If $1/n \leq \phi \leq \pi - 1/n$, we have, with notation as in Lemma 4.

$$N(\phi) = \frac{O(1)}{(p * q)_n} \sum_{k=0}^{n-1} p_k q_{n-k} (n-k)^{\alpha+1/2} \left(\sin \frac{\phi}{2} \right)^{-\alpha-3/2} \\ \left(\cos \frac{\phi}{2} \right)^{-\beta-1/2} \left[\cos \{(n-k)\phi + \rho\phi - r\} + \frac{O(1)}{(n-k) \sin \phi} \right]$$

Since, for fixed n , q_{n-k} is non-increasing, we can deal with the first term on the right by first using the second mean value theorem and then applying Lemma 4.

To deal with second term on the right we apply the result of Lemma 7, and this proves (4.12).

§5. Proof of the theorem : Following Obreckkoff⁴ the n th partial sum of the series (2.1) at the point $x = 1$ is given by

$$S_n(1) = 2^{\alpha+\beta+1} \int_0^\pi \left(\sin \frac{\phi}{2} \right)^{2\alpha+1} \left(\cos \frac{\phi}{2} \right)^{2\beta+1} f(\cos \phi) S'_n(1, \cos \phi) d\phi$$

where $S'_n(1, \cos \phi)$ denotes the n -th partial sum of the series

$$\sum_m \frac{P_m^{(\alpha, \beta)}(1) P_m^{(\alpha, \beta)}(\cos \phi)}{g_m}$$

where

$$g_n = \frac{(2n + \alpha + \beta + 1) \Gamma(n + 1) \Gamma(n + \alpha + \beta + 1)}{2^{\alpha+\beta+1} \Gamma(n + \alpha + 1) \Gamma(n + \beta + 1)}.$$

Rao⁶ has shown that

$$S'_n(1, \cos \phi) = \lambda_n P_n^{(\alpha+1, \beta)}(\cos \phi).$$

Therefore

$$S_n(1) - A = 2^{\alpha+\beta+1} \lambda_n \int_0^\pi \left(\sin \frac{\phi}{2} \right)^{2\alpha+1} \left(\cos \frac{\phi}{2} \right)^{2\beta+1} \{f(\cos \phi) - A\}$$

$$P_n^{(\alpha+1, \beta)}(\cos \phi) d\phi$$

$$= 2^{\alpha+\beta+1} \lambda_n \int_0^\pi F(\phi) P_n^{(\alpha+1, \beta)}(\cos \phi) d\phi$$

where λ_n is defined as in Lemma 8.

The (N, p, q) means of the series (2.1) at $x = 1$ is given by

$$t_n^{p,q} = \frac{1}{(p * q)_n} \sum_{k=0}^n p_k q_{n-k} S_{n-k}(1)$$

or

$$\begin{aligned} t_n^{p,q} - A &= \frac{1}{(p * q)_n} \sum_{k=0}^n p_k q_{n-k} \{S_{n-k}(1) - A\} \\ &= \int_0^\pi F(\phi) N(\phi) d\phi + \frac{p_n q_0}{(p * q)_n} \int_0^\pi F(\phi) d\phi \end{aligned}$$

Since $\int_0^\pi F(\phi) d\phi$ is a finite constant, by assumption, second term on the right is $o(1)$ as $n \rightarrow \infty$. Hence in order to prove theorem we have to show that

$$I = \int_0^\pi F(\phi) N(\phi) d\phi = o(1) \text{ as } n \rightarrow \infty.$$

Let us write

$$I = \left[\int_0^{1/n} + \int_{1/n}^{\delta} + \int_{\delta}^{\pi-1/n} + \int_{\pi-1/n}^{\pi} \right] d\phi$$

$$= I_1 + I_2 + I_3 + I_4, \text{ say.}$$

where δ is a suitable chosen constant. Now

$$I_1 = \int_0^{1/n} |F(\phi)| O(n^{2\alpha+2}) d\phi \text{ from (4.10)}$$

$$= O(n^{2\alpha+2}) o\left(\frac{n^{-2\alpha-2}}{\log n}\right)$$

$$= o(1), \text{ as } n \rightarrow \infty.$$

Coming to I_2 , we have

$$I_2 = O\left(\frac{q_n n^{\alpha+1/2}}{(p * q)_n}\right) \int_{1/n}^{\delta} \frac{|F(\phi)| P(1/\phi)}{\phi^{(2\alpha+3)/2}} d\phi$$

$$+ O(n^{\alpha-1/2}) \int_{1/n}^{\delta} \frac{|F(\phi)|}{\phi^{(2\alpha+5)/2}} d\phi.$$

$$= I_{2,1} + I_{2,2} \text{ say}$$

Given $\epsilon > 0$, let δ be chosen so that

$$|F_1(\phi)| \leq \frac{\epsilon \phi^{2\alpha+2}}{\log(1/\phi)} \cdot O < \phi \leq \delta.$$

Then

$$|I_{2,1}(\phi)| \leq \frac{M q_n n^{\alpha+1/2}}{(p * q)_n} \int_{1/n}^{\delta} \frac{|F(\phi) P[1/\phi]|}{\phi^{(2\alpha+3)/2}} d\phi$$

where M is a positive constant, which may be different at each occurrence. Hence

$$|I_{2,1}| \leq \frac{M q_n n^{\alpha+1/2}}{(p * q)_n} \left\{ \left[\frac{F_1(\phi) P[1/\phi]}{\phi^{(2\alpha+3)/2}} \right]_{1/n}^{\delta} - \int_{1/n}^{\delta} F_1(\phi) \right.$$

$$\left. \times d\left(\frac{P[1/\phi]}{\phi^{(2\alpha+3)/2}} \right) \right\}$$

$$= I_{2,1,1} + I_{2,1,2} \text{ say.}$$

If $M(\delta)$ denotes a constant depending on δ , we see that, for fixed δ .

$$\begin{aligned} I_{2,1,1} &= \frac{M(\delta) q_n n^{\alpha+1/2}}{(p * q)_n} + o\left(\frac{q_n P_n}{(p * q)_n \log n}\right) \\ &= o(1) \text{ (by Lemma 3 and (3.2))} \end{aligned}$$

and

$$\begin{aligned} I_{2,1,2} &\leq \frac{M \epsilon q_n n^{\alpha+1/2}}{(p * q)_n} \int_{1/n}^{\delta} \frac{\phi^{2\alpha+2}}{\log(1/\alpha)} \left| d\left(\frac{P_{[1/\phi]}}{\phi^{(2\alpha+3)/2}}\right) \right| \\ &= \frac{M \epsilon q_n n^{\alpha+1/2}}{(p * q)_n} \int_{1/\delta}^n \frac{x^{-2\alpha-2}}{\log x} d\{P_{[x]} x^{(2\alpha+3)/2}\} \\ &= \frac{M \epsilon q_n n^{\alpha+1/2}}{(p * q)_n} \int_{1/\delta}^n \frac{x^{-2\alpha-2}}{\log x} \{x^{(2\alpha+3)/2} dP_{[x]} \\ &\quad + (2\alpha + 3)/2 \cdot x^{(2\alpha+1)/2} P_{[x]} dx\} \\ &= \frac{M \epsilon q_n n^{\alpha+1/2}}{(p * q)_n} \left[\int_{1/\delta}^n \frac{x^{-(2\alpha+1)/2}}{\log x} dP_{[x]} \right. \\ &\quad \left. + (2\alpha + 3)/2 \cdot \int_{1/\delta}^n \frac{x^{-(2\alpha+3)/2}}{\log x} P_{[x]} dx \right] \\ &= \frac{M \epsilon q_n n^{\alpha+1/2}}{(p * q)_n} [J + (2\alpha + 3)/2K], \text{ say.} \end{aligned}$$

Since $P_{(x)}$ has a jump of p_k at $x = k$ (and is elsewhere constant).

$$\begin{aligned} J &= \sum_{k=0}^n \frac{p_k}{k^{(2\alpha+1)/2} \log k} \text{ where } c \text{ is a fixed positive constant} \\ &= O\left(\sum_{k=0}^n \frac{P_k}{k^{(2\alpha+3)/2} \log k}\right) \end{aligned}$$

Also

$$K \leq \sum_{k=c-1}^{n-1} P_k \int_k^{k+1} \frac{x^{-(2\alpha+3)/2}}{\log x} dx$$

$$= O \left\{ \sum_{k=\epsilon-1}^{n-1} \frac{P_k}{k^{(2\alpha+3)/2} \log k} \right\}.$$

Hence

$$| I_{2,1,2} | \leq M \epsilon. \text{ from (3.1).}$$

Now

$$\begin{aligned} | I_{2,2} | &\leq M n^{\alpha-1/2} \int_{1/n}^{\delta} | F(\phi) | \phi^{-(2\alpha+5)/2} d\phi \\ &= n^{\alpha-1/2} \left\{ M [F_1(\phi) \phi^{-(2\alpha+5)/2}]_{1/n}^{\delta} + M \int_{1/n}^{\delta} F_1(\phi) \phi^{-(2\alpha+7)/2} d\phi \right\} \end{aligned}$$

(The two M 's may be different)

$$= I_{2,2,1} + I_{2,2,2}, \text{ say.}$$

Therefore

$$\begin{aligned} I_{2,2,1} &= M(\delta) n^{\alpha-1/2} + o(1) \\ &= o(1), \text{ as } n \rightarrow \infty \end{aligned}$$

and

$$\begin{aligned} | I_{2,2,2} | &\leq M \epsilon n^{\alpha-1/2} \int_{1/n}^{\delta} \frac{\phi^{\alpha-3/2}}{(\log(1/\phi))} d\phi \\ &= M \epsilon n^{\alpha-1/2} \int_{1/\delta}^n \frac{x^{-(2\alpha+1)/2}}{\log x} dx \\ &\leq M \epsilon \text{ because } \alpha < 1/2. \end{aligned}$$

Thus

$\lim_{n \rightarrow \infty} \text{Sup } | I_2 |$ can be made arbitrarily small by choice of δ and thus it is enough to prove that, having fixed δ , we have $I_3 \rightarrow 0$, $I_4 \rightarrow 0$, as $n \rightarrow \infty$. Take, then, δ as fixed. Then

$$\begin{aligned} I_3 &= O \left(\frac{q_n n^{\alpha+1/2}}{(p * q)_n} \right) \int_{\delta}^{\pi-1/n} | F(\phi) | \left(\sin \frac{\phi}{2} \right)^{-\alpha-3/2} \left(\cos \frac{\phi}{2} \right)^{-\beta-1/2} \\ &\quad \times P_{[1/\phi]} d\phi \end{aligned}$$

$$\begin{aligned}
 & + O(n^{\alpha-1/2}) \int_{\delta}^{\pi-1/n} |F(\phi)| \left(\sin \frac{\phi}{2}\right)^{-\alpha-5/2} \left(\cos \frac{\phi}{2}\right)^{-\beta-3/2} d\phi \\
 & = I_{3,1} + I_{3,2}, \text{ say.}
 \end{aligned}$$

Since $(\sin \frac{\phi}{2})^{-\alpha-3/2}$ is bounded for $\delta \leq \phi \leq \pi$ and since $P_{[1/\phi]}$ is bounded and $-\beta - \frac{1}{2} > -\beta - \alpha - 1$. We have

$$\begin{aligned}
 I_{3,1} & = O\left(\frac{q_n n^{\alpha+1/2}}{(p * q)_n}\right) \int_{\delta}^{\pi-1/n} |F(\phi)| \left(\cos \frac{\phi}{2}\right)^{-\alpha-\beta-1} d\phi \\
 & = O\left(\frac{q_n n^{\alpha+1/2}}{(p * q)_n}\right) \text{ by} \quad \dots(4.4)
 \end{aligned}$$

$$= o(1) \text{ as } n \rightarrow \infty. \text{ by} \quad \dots(4.5)$$

We divide $I_{3,2}$ into $\int_{\delta}^{\delta'}$ and $\int_{\delta'}^{\pi-1/n}$

Given any $\epsilon' > 0$ we can choose δ' so that

$$\int_{\delta'}^{\pi} \left(\cos \frac{\phi}{2}\right)^{-\alpha-\beta-1} |F(\phi)| d\phi \leq \epsilon'.$$

The contribution to $I_{3,2}$ of the range $(\delta', \pi - 1/n)$ is less than or equal a to constant times

$$\begin{aligned}
 & n^{\alpha-1/2} \int_{\delta'}^{\pi-1/n} |F(\phi)| \left(\cos \frac{\phi}{2}\right)^{-\beta-3/2} d\phi \\
 & = n^{\alpha-1/2} \int_{\delta'}^{\pi-1/n} |F(\phi)| \left(\cos \frac{\phi}{2}\right)^{-\beta-\alpha-1} \left(\cos \frac{\phi}{2}\right)^{\alpha-1/2} d\phi \\
 & \leq M \epsilon'.
 \end{aligned}$$

Since in the range considered $\left(\cos \frac{\phi}{2}\right)^{\alpha-1/2}$ is $O\left(\left(\frac{1}{n}\right)^{\alpha-1/2}\right)$. Thus the lim sup of the contribution of this range can be made arbitrarily small by choice of ϵ' . So that it is enough to prove that for fixed δ' , the contribution of the range (δ', δ') tends to 0. But for fixed δ' ,

$$\int_{\delta}^{\delta'} |F(\phi)| \left(\sin \frac{\phi}{2}\right)^{-\alpha-5/2} \left(\cos \frac{\phi}{2}\right)^{-\beta-3/2} d\phi$$

is a constant, so the contribution is

$$O(n^{\alpha-1/2}) \rightarrow 0, \alpha < 1/2.$$

Finally

$$I_4 = O(n^{\alpha+\beta+1}) \int_{\pi-1/n}^{\pi} |F(\phi)| d\phi.$$

But $n^{\alpha+\beta+1} = O\left(\left(\cos \frac{\phi}{2}\right)^{-\alpha-\beta-1}\right)$ uniformly in $\pi - 1/n \leq \phi \leq \pi$, whence it follows at once that $I_4 \rightarrow 0$.

This completes the proof of the theorem.

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APPROXIMATION OF A FUNCTION BY THE $F(a, q)$ TRANSFORM OF ITS FOURIER SERIES

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Results on the order of approximation of a 2π -periodic continuous function by the Euler or Taylor means of the sequence of partial sums of its Fourier series are extended to general class of $F(a, q)$ transform of which these and other transforms known as Kreisverfahren are special cases.

1. INTRODUCTION

Let $C[0, 2\pi]$ denote the class of all continuous 2π periodic functions. If $f \in C[0, 2\pi]$, ω_f denotes its modulus of continuity. Let the Fourier series associated with $f \in C[0, 2\pi]$ at x be

$$a_0/2 + \sum_{n=1}^{\infty} (a_n \cos nx + b_n \sin nx). \quad \dots(1.1)$$

As usual let us write

$$\phi_x(t) = \frac{1}{2} \{f(x+t) + f(x-t) - 2f(x)\}. \quad \dots(1.2)$$

The k th partial sum $s_k(x)$ of the Fourier series is given by

$$s_k(x) - f(x) = \frac{1}{\pi} \int_0^{\pi} \frac{\phi_x(t)}{\sin \frac{1}{2}t} \sin(k + \frac{1}{2})t dt. \quad \dots(1.3)$$

The family $F(a, q)$ of summability methods was introduced by Meir⁶. An $F(a, q)$ -transform of the sequence $\{s_k(x)\}$, the sequence of partial sums of the Fourier series of $f \in C[0, 2\pi]$ at x , is

$$\sigma_p(x) = \sigma_p(a, q, f, x) = \sum_{k=0}^{\infty} c_k(p) s_k(x), \quad c_k(p) \geq 0 \quad \dots(1.4)$$

where, for $g(q, k)$ defined by

$$g(q, k) = \sqrt{a/\pi q} \exp \{-aq^{-1}(k - q)^2\}, \quad a > 0, \quad q = q(p) \quad \dots(1.5)$$

which is a positive non-decreasing function of a continuous or discrete parameter p , which tends to infinity as $p \rightarrow \infty$, and for some fixed γ , $\frac{1}{2} < \gamma < \frac{2}{3}$,

$$c_k(p) = q(q, k) \left\{ 1 + O\left(\frac{|k - q| + 1}{q}\right) + O\left(\frac{|k - q|^3}{q^2}\right) \right\} \quad \dots(1.6)$$

as $p \rightarrow \infty$ uniformly in k for $|k - q| \leq q^\gamma$, while

$$\sum_{|k - q| > q^\gamma} (k + 1) c_k(p) = O\{\exp(-q^\mu)\} \quad \dots(1.7)$$

as $p \rightarrow \infty$, for some positive number μ independent of p .

The family $F(a, q)$ is known⁵ to contain the summability methods of generalised Borel, Euler, Taylor, S_β (defined explicitly later) and Valiron. It is known⁵ that

$$\sum_{k=0}^{\infty} c_k(p) = 1 + O(q^{-1/2}). \quad \dots(1.8)$$

The summability methods of Euler, Taylor, S_β and Borel satisfy (1.8) in the stronger form

$$\sum_{k=0}^{\infty} c_k(p) = 1. \quad \dots(1.9)$$

In what follows ω is a positive non-decreasing function such that

$$\omega(t)/t^{1/2} \text{ is non-increasing function of } t \in [0, \pi]. \quad \dots(1.10)$$

As a consequence of this condition (1.10) on ω , for $\lambda > 1$, we get

$$\omega(\lambda t) \leq \gamma \lambda \omega(t) \quad (t > 0). \quad \dots(1.11)$$

In the sequel in order relations involving q it is to be understood that $p \rightarrow \infty$.

Chui and Holland¹ proved that the order of approximation of functions in the class $\text{Lip } \alpha$ by either Euler- $(E, 1)$ means or Taylor means of Fourier series can be reduced to Jackson order provided, in each case, a suitable integrability condition is imposed upon $\phi_x(t)$. Xie⁸ extended this result to Euler- (E, q) ($q > 0$ means in the context of continuous 2π periodic functions Chui *et al.*³ (p.373, Corollary 5.15) seem to have obtained the analogue of the above result for the Borel method, but the details do not seem to have been published. We append the details pertaining to the analogue for the S_β method in Theorem 2. We extend this result to the family $F(a, q)$ in the context of the class $\text{Lip } \alpha$, but with the restriction $0 < \alpha \leq \frac{1}{2}$.

We prove the following results

Theorem 1 — Let n be the integral part of $q = q(p)$. Set $m = n + 1$. Let $f \in C[0, 2\pi]$ such that $\omega_f \geq \omega$, and satisfy the condition

$$\int_{u(m)}^{v(m)} \frac{|\phi_x(t) - \phi_x(t + u(m))|}{t} \exp(-mt^2/4a) dt = O\left(\omega\left(\frac{1}{m}\right)\right) \quad (1.12)$$

uniformly in x . Then

$$\max_{0 \leq x \leq 2\pi} |\sigma_p(x) - f(x)| = O\left(\omega\left(\frac{1}{m}\right)\right) \quad \dots(1.13)$$

where

$$u(m) = \pi/m + \frac{1}{2}, v(m) = [u(m)]^\eta, 0 < \eta < \frac{1}{2}. \quad \dots(1.14)$$

In view of (1.10), Theorem 1 immediately yields the

Corollary--If $\omega(t) = t^\alpha$, $0 < \alpha \leq \frac{1}{2}$ and $f \in C[0, 2\pi]$ such that $\omega_f \leq \omega$ and satisfy the condition (1.12) uniformly in x , then

$$\max_{0 \leq x \leq 2\pi} |\sigma_p(x) - f(x)| = O(m^{-\alpha}). \quad \dots(1.15)$$

This corollary with the restriction on α weakened to $0 < \alpha < 1$, is due to Chui and Holland¹ for the methods of Euler-($E, 1$) and Taylor and due to Xie⁸ for the method of Euler (E, q) ($q > 0$). The following Theorem 2 is the analogue of these results for the method S_β ($0 < \beta < 1$) for which the transform $\sigma_p \equiv S_\beta^p$ of the sequence $\{s_k\}$ is defined with

$$c_k(p) = (1 - \beta)^{p+1} \binom{p+k}{k} \beta^k, k, p = 0, 1, 2, \dots$$

Theorem 2--Let $f \in \text{Lip } \alpha$, $0 < \alpha < 1$. Let S_β^p ($p = 0, 1, 2, \dots$) denote the p th S_β -mean of the Fourier series,

If

$$\int_{a(p)}^{b(p)} \frac{|\phi_x(t) - \phi_x(t + a(p))|}{t} \exp\left\{-\frac{1}{2} p\beta (t/1-\beta)^2\right\} dt = O(p^{-\alpha}), \quad \dots(1.16)$$

where

$$a(p) = \frac{\pi(1-\beta)}{(p+1)\beta}, b(p) = [a(p)]^\delta, \frac{1+\alpha}{3+\alpha} < \delta < \frac{1}{2}, \text{ then}$$

$$\max_{0 \leq x \leq 2\pi} |S_\beta^p(x) - f(x)| = O(p^{-\alpha}). \quad \dots(1.17)$$

2. PRELIMINARY RESULTS

To prove the results in section 1 we need the following lemmas.

Lemma 1—If $q = q(p)$ is an integer valued function of p , then, for $\frac{1}{2} < \gamma < \frac{2}{3}$ we have

$$\begin{aligned} & \int_0^\pi \frac{\phi_x(t)}{\sin t/2} \sum_{|k-q| \leq q^\gamma} g(q, k) \sin(k + \tfrac{1}{2})t \, dt \\ &= \int_0^\pi \frac{\phi_x(t)}{\sin t/2} \exp(-qt^2/4a) \sin(q + \tfrac{1}{2})t \, dt \\ & \quad + O(q^{3\gamma/2} \exp(-aq^{2\gamma-1})). \end{aligned} \quad \dots(2.1)$$

PROOF : Following the proof of Lemma 3.2 of Ikeno⁴ we have

$$\begin{aligned} & \sum_{|k-q| \leq q^\gamma} g(q, k) \sin(k + \tfrac{1}{2})t \, dt \\ &= \exp(-qt^2/4a) \sin(q + \tfrac{1}{2})t \\ & \quad + O\left\{ \sum_{|r| > q^\gamma} \sqrt{a/\pi q} \exp(-ar^2/q) |\sin(r + q + \tfrac{1}{2})t| \right\}, \end{aligned}$$

where $r = k - q$. Now we estimate the error term :

$$\begin{aligned} & \sum_{|r| > q^\gamma} \sqrt{a/\pi q} \exp(-ar^2/q) |\sin(r + q + \tfrac{1}{2})t| \\ & \leq \sum_{|r| > q^\gamma} \sqrt{a/\pi q} \exp(-ar^2/q) (|r| + q + \tfrac{1}{2})t \\ &= 2\sqrt{a/\pi q} t \left\{ \sum_{r > q^\gamma} r \exp(-ar^2/q) \right. \\ & \quad \left. + (q + \tfrac{1}{2}) \sum_{r > q^\gamma} \exp(-ar^2/q) \right\}. \end{aligned}$$

Now, for large q ,

$$\begin{aligned} \sum_{r > q^\gamma} r \exp(-ar^2/q) &\leq q^\gamma \exp(-aq^{2\gamma-1}) + \int_{q^\gamma}^\infty y \exp(-ay^2/q) \, dy \\ &= q^\gamma \exp(-aq^{2\gamma-1}) + \frac{q}{2a} \int_{a q^{2\gamma-1}}^\infty e^{-z} \, dz. \end{aligned}$$

Using the fact that, for real θ

$$\int_\lambda^\infty z^\theta e^{-z} \, dz = O(\lambda^\theta e^{-\lambda}), \text{ as } \lambda \rightarrow \infty \quad \dots(2.2)$$

we get

$$\sum_{r > q^\gamma} r \exp(-ar^2/q) \leq q^\gamma \exp(-aq^{2\gamma-1}) + O(q \exp(-aq^{2\gamma-1})).$$

Similarly, we can prove

$$\sum_{r > q^\gamma} \exp(-ar^2/q) \leq \exp(-aq^{2\gamma-1}) + O(q^{1-\gamma} \exp(-aq^{2\gamma-1})).$$

Thus

$$\begin{aligned} \sum_{|r| > q^\gamma} \sqrt{a/\pi q} \exp(-ar^2/q) |\sin(r + q + \tfrac{1}{2})t| \\ = O(\sqrt{q} t \exp(-aq^{2\gamma-1})) + O(q^{(3-2\gamma/2)} t \exp(-aq^{2\gamma-1})). \end{aligned}$$

Hence the lemma follows in view of boundedness of $\phi_x(t)$ and since $\sin\left(\frac{t}{2}\right) > \left(\frac{t}{\pi}\right)$ ($0 < t < \pi$).

Lemma 2—Let $f \in C[0, 2\pi]$ such that $\omega_f \leq \omega$, where ω is as in section 1, and let condition (1.12) be satisfied. Then

$$\int_0^\pi \frac{\phi_x(t)}{\sin t/2} \exp(-mt^2/4a) \sin(m + \tfrac{1}{2})t dt = O(\omega(\tfrac{1}{m})).$$

PROOF : If u and v are as defined in (1.14) we write

$$\begin{aligned} \int_0^\pi \frac{\phi_x(t)}{\sin t/2} \exp(-mt^2/4a) \sin(m + \tfrac{1}{2})t dt \\ = \left(\int_0^{u(m)} + \int_{u(m)}^{v(m)} + \int_{v(m)}^\pi \right) \frac{\phi_x(t)}{\sin t/2} \exp(-mt^2/4a) \sin(m + \tfrac{1}{2})t dt \\ = J_1 + J_2 + J_3, \text{ say.} \end{aligned} \quad \dots(2.3)$$

Now

$$\begin{aligned} |J_1| &\leq \pi \int_0^{u(m)} \frac{|\phi_x(t)|}{t} \exp(-mt^2/4a) \sin(m + \tfrac{1}{2})t dt \\ &\leq \pi \int_0^{u(m)} \frac{\omega(t)}{(t)} (m + \tfrac{1}{2})t dt \\ &\leq \pi^2 \omega(u(m)) = O(\omega(\tfrac{1}{m})). \end{aligned} \quad \dots(2.4)$$

Using (2.2) we estimate J_3 :

$$\begin{aligned}
 |J_3| &\leq \pi \int_{v(m)}^{\pi} \frac{|\phi_x(t)|}{t} \exp(-mt^2/4a) dt \\
 &= O \left\{ \int_{v(m)}^{\infty} 1/t \exp(-mt^2/4a) dt \right\} \\
 &= O \left\{ \int_{\frac{m[v(m)]^2}{4a}}^{\infty} \frac{1}{z} e^{-z} dz \right\} \\
 &= O \{ m^{2\eta-1} \exp(-\frac{\pi^{2\eta}}{4a} m^{1-2\eta}) \}. \quad \dots(2.5)
 \end{aligned}$$

Now, for $\alpha > 0$, $A > 0$, λ and δ any real constants we have

$$m^\lambda \exp(-Am^\alpha) = O(m^\delta). \quad \dots(2.6)$$

Also, by the condition (1.10) on ω ,

$$q^{-1/2}, m^{-1/2} = O(\omega(\frac{1}{m})). \quad \dots(2.7)$$

Thus it is enough to show that

$$|J_2| = O(\omega(\frac{1}{m})).$$

Since

$$\operatorname{cosec} t - \frac{1}{t} = O(t)$$

with (1.10), we have

$$\begin{aligned}
 J_2 &= \int_{u(m)}^{v(m)} \frac{\phi_x(t)}{\sin \frac{1}{2}t} \exp(-mt^2/4a) \sin(m + \frac{1}{2}t) dt \\
 &= 2 \int_{u(m)}^{v(m)} \frac{\phi_x(t)}{t} \exp(-mt^2/4a) \sin(m + \frac{1}{2}t) t dt \\
 &\quad + \int_{u(m)}^{v(m)} \phi_x(t) (\operatorname{cosec} \frac{t}{2} - \frac{2}{t}) \exp(-mt^2/4a) \sin(m + \frac{1}{2}t) t dt
 \end{aligned}$$

(equation continued on p. 375)

$$\begin{aligned}
 &= 2 \int_{u(m)}^{v(m)} \frac{\phi_x(t)}{t} \exp(-mt^2/4a) \sin(m + \tfrac{1}{2}) t dt + O(\omega \frac{1}{m}) \\
 &= J_4 + O(\omega (\frac{1}{m})), \text{ say.} \quad \dots(2.8)
 \end{aligned}$$

We shall write J_4 as follows :

$$\begin{aligned}
 J_4 &= \int_{u(m)}^{v(m)} \frac{\phi_x(t)}{t} \exp(-mt^2/4a) \sin(m + \tfrac{1}{2}) t dt \\
 &\quad - \int_0^{v(m)-u(m)} \frac{\phi_x(t+u(m))}{t+u(m)} \exp(-m(t+u(m))^2/4a) \\
 &\quad \times \sin(m + \tfrac{1}{2}) t dt \\
 &= \int_{u(m)}^{v(m)} \frac{\phi_x(t) - \phi_x(t+u(m))}{t} \exp(-mt^2/4a) \sin(m + \tfrac{1}{2}) t dt \\
 &\quad + \int_{u(m)}^{v(m)} \frac{\phi_x(t+u(m))}{t} [\exp(-mt^2/4a) \\
 &\quad - \exp(-m(t+u(m))^2/4a)] \sin(m + \tfrac{1}{2}) t dt \\
 &\quad + \int_{u(m)}^{v(m)} \phi_x(t+u(m)) \exp(-m(t+u(m))^2/4a) \left[\frac{1}{t} \right. \\
 &\quad \left. - \frac{1}{t+u(m)} \right] \sin(m + \tfrac{1}{2}) t dt \\
 &\quad - \int_0^{u(m)} \frac{\phi_x(t+u(m))}{t+u(m)} \exp(-m(t+u(m))^2/4a) \sin(m + \tfrac{1}{2}) t dt \\
 &\quad + \int_{v(m)-u(m)}^{v(m)} \frac{\phi_x(t+u(m))}{t+u(m)} \exp(-m(t+u(m))^2/4a) \sin \\
 &\quad (m + \tfrac{1}{2}) t dt = I_1 + I_2 + I_3 + I_4 + I_5.
 \end{aligned}$$

By hypothesis

$$I_1 = O\left(\omega\left(\frac{1}{m}\right)\right). \quad \dots(2.9)$$

By mean value theorem

$$\exp(-mt^2/4a) - \exp(-m(t+u(m))^2/4a) = \frac{2u(m)m\theta}{4a} \exp(-m\theta^2/4a)$$

for some θ such that $t < \theta < t + u(m) < 2t$. Hence

$$\exp(-mt^2/4a) - \exp(-m(t+u(m))^2/4a) = O(t \exp(-mt^2/4a)).$$

Thus

$$|I_2| = O\left\{\int_{u(m)}^{v(m)} |\phi_x(t+u(m))| \exp(-mt^2/4a) dt\right\}.$$

By (1.10) and (1.11), we have

$$\begin{aligned} |I_2| &= O\left\{\sqrt{m} \omega\left(\frac{1}{m}\right) \int_{u(m)}^{v(m)} t^{1/2} \exp(-mt^2/4a) dt\right\} \\ &= O\left(\omega\left(\frac{1}{m}\right)\right). \end{aligned} \quad \dots(2.10)$$

Again, by (1.10) and (1.11) we have

$$\begin{aligned} |I_3| &\leq u(m) \int_{u(m)}^{v(m)} \frac{|\phi_x(t+u(m))|}{t(t+u(m))} dt \\ &= O\left\{u(m) \sqrt{m} \omega\left(\frac{1}{m}\right) \int_{u(m)}^{v(m)} \frac{1}{t(t+u(m))^{1/2}} dt\right\} \\ &= O\left(\omega\left(\frac{1}{m}\right)\right). \end{aligned} \quad \dots(2.11)$$

Also,

$$\begin{aligned} |I_4| &\leq \int_0^{u(m)} \frac{|\phi_x(t+u(m))|}{t+u(m)} |\sin(m+\frac{1}{2})t| dt \\ &\leq \int_{u(m)}^{2u(m)} \frac{|\phi_x(t)|}{t} (m+\frac{1}{2})t dt \end{aligned}$$

(equation continued on p. 377)

$$\begin{aligned} &\leq (m + \tfrac{1}{2}) \int_{u(m)}^{2u(m)} \omega(t) dt \\ &\leq \pi \omega(2u(m)) = O\left(\omega\left(\frac{1}{m}\right)\right). \end{aligned} \quad \dots(2.12)$$

Finally,

$$\begin{aligned} |I_5| &\leq \int_{v(m)-u(m)}^{v(m)} \frac{|\phi_x(t+u(m))|}{t+u(m)} dt \\ &= \int_{v(m)}^{v(m)+u(m)} \frac{|\phi_x(t)|}{t} dt. \end{aligned}$$

By (1.10) and (1.11) we have

$$|I_5| = O\left\{\sqrt{M} \omega\left(\frac{1}{m} \int_{v(m)}^{v(m)+u(m)} t^{-1/2} dt\right)\right\}.$$

But

$$\begin{aligned} [v(m) + u(m)]^{1/2} - [v(m)]^{1/2} &= [v(m)]^{1/2} \left\{ \left(1 + \frac{u(m)}{v(m)}\right)^{1/2} - 1 \right\} \\ &= O\{[u(m)]^{1/2}\}. \end{aligned}$$

Thus

$$|I_5| = O\left(\omega\left(\frac{1}{m}\right)\right). \quad \dots(2.13)$$

Hence the lemma follows from (2.3) to (2.13).

Lemma 3—Let $0 < \beta < 1$, $0 < t \leq \pi$ and let ρ , θ , t and β satisfy

$$\rho_{\theta}^{-it} = 1 - \beta e^{-it} \quad \dots(2.14)$$

Then, for $p = 0, 1, 2, \dots$,

$$(i) \quad \left| \theta - \frac{\beta t}{1 - \beta} \right| \leq Ct^3 \quad \dots(2.15)$$

$$(ii) \quad \left(\frac{1 - \beta}{\rho}\right)^p \leq \exp(-Apt^2) \quad \dots(2.16)$$

where C and A are positive constants depending on β , and

$$(iii) \quad \left(\frac{1 - \beta}{\rho}\right)^p - \exp\left(\frac{1}{2} p \beta \left(\frac{t}{1 - \beta}\right)^2\right) = O(pt^4). \quad \dots(2.17)$$

These results are known. For example, for (i) see Miracle⁷ and for (ii) and (iii) see Forbes².

3. PROOF OF THE RESULTS

Proof of Theorem 1—By (1.3), (1.4) and (1.8) we get

$$\begin{aligned}\sigma_p(x) - f(x) &= \frac{1}{\pi} \int_0^\pi \frac{\phi_x(t)}{\sin \frac{1}{2}t} \sum_{k=0}^\infty c_k(p) \sin(k + \tfrac{1}{2})t \, dt + O(q^{-1/2}) \\ &= \frac{1}{\pi} \int_0^\pi \frac{\phi_x(t)}{\sin \frac{1}{2}t} \left[\left(\sum_{|k-q| \leq q^\gamma} + \sum_{|k-q| > q^\gamma} \right) \right. \\ &\quad \left. \times c_k(p) \sin(k + \tfrac{1}{2})t \right] dt + O(q^{-1/2}) \\ &= S_1 + S_2 + O(q^{-1/2}).\end{aligned}\quad \dots(3.1)$$

We first estimate S_2 :

$$\begin{aligned}|S_2| &\leq \int_0^\pi \frac{|\phi_x(t)|}{t} \sum_{|k-q| > q^\gamma} c_k(p) (k + \tfrac{1}{2}) t \, dt \\ &= O(\exp(-q^\mu)) \text{ (by (1.7)).}\end{aligned}\quad \dots(3.2)$$

Using (1.6), S_1 can be written as follows :

$$\begin{aligned}S_1 &= \frac{1}{\pi} \int_0^\pi \frac{\phi_x(t)}{\sin \frac{1}{2}t} \sum_{|k-q| \leq q^\gamma} g(q, k) \left\{ 1 + O\left(\frac{|k-q|+1}{q}\right) \right. \\ &\quad \left. + O\left(\frac{|k-q|^3}{q^2}\right) \right\} \sin(k + \tfrac{1}{2})t \, dt \\ &= S_3 + S_4 + S_5, \text{ say.}\end{aligned}\quad \dots(3.3)$$

We estimate S_4 and S_5 by splitting the integral into two parts and using condition (1.10) and properties of sine function.

$$\begin{aligned}|S_3| &\leq \left(\int_0^{1/q} + \int_{1/q}^\pi \right) \frac{\phi_x(t)}{t} \sum_{|k-q| \leq q^\gamma} g(d, k) O\left(\frac{|k-q|+1}{q}\right) \\ &\quad \times \sin(k + \tfrac{1}{2})t \, dt\end{aligned}$$

(equation continued on p. 379)

$$\begin{aligned}
 &= O \left\{ \int_0^{1/q} |\phi_x(t)| \sum_{|k-q| \leq q^\gamma} g(q, k) O \left(\frac{|k-q|+1}{q} \right) \right. \\
 &\quad \times (|k-q| + q + \tfrac{1}{2}) dt \Big\} \\
 &\quad + O \left\{ \int_{1/q}^{\pi} \frac{|\phi_x(t)|}{t} \sum_{|k-q| \leq q^\gamma} g(q, k) \left(\frac{|k-q|+1}{q} \right) \right. \\
 &\quad \left. dt \right\} \\
 &= O \left\{ \sqrt{q} \int_0^{1/q} |\phi_x(t)| dt \right\} + O \left\{ \frac{1}{\sqrt{q}} \int_{1/q}^{\pi} \frac{|\phi_x(t)|}{t} dt \right\} \\
 &= O \left(\omega \left(\frac{1}{q} \right) \right). \quad \dots(3.4)
 \end{aligned}$$

Similarly,

$$|S_5| = O \left(\omega \left(\frac{1}{q} \right) \right). \quad \dots(3.5)$$

Since $m = m(p)$ is an integer valued function of p , by Lemmas 1 and 2 we have

$$\begin{aligned}
 &\frac{1}{\pi} \int_0^{\pi} \frac{\phi_x(t)}{\sin \frac{1}{2}t} \sum_{|k-m| \leq m^\gamma} g(m, k) \sin(m + \tfrac{1}{2})t dt \\
 &= \frac{1}{\pi} \int_0^{\pi} \frac{\phi_x(t)}{\sin \frac{1}{2}t} \exp(-mt^2/4a) \sin(m + \tfrac{1}{2})t dt \\
 &\quad + O(m^{3/2-\gamma} \exp(-am^{2\gamma-1})) \\
 &= O \left(\omega \left(\frac{1}{m} \right) \right). \quad \dots(3.6)
 \end{aligned}$$

Now we shall estimate the difference :

$$\int_0^{\pi} \frac{\phi_x(t)}{\sin \frac{1}{2}t} \sum_{|k-q| \leq q^\gamma} g(q, k) \sin(k + \tfrac{1}{2})t dt$$

(equation continued on p. 380)

$$\begin{aligned}
& - \int_0^\pi \frac{\phi_x(t)}{\sin \frac{1}{2}t} \sum_{|k-m| \leq m^\gamma} g(m, k) \sin(k + \frac{1}{2})t \, dt \\
& = \int_0^\pi \frac{\phi_x(t)}{\sin \frac{1}{2}t} \sum_{m \leq k < m+m^\gamma} (g(q, k) - g(m, k)) \sin(k + \frac{1}{2})t \, dt \\
& \quad + \int_0^\pi \frac{\phi_x(t)}{\sin \frac{1}{2}t} \sum_{m-m^\gamma \leq k < m} (g(q, k) - g(m, k)) \sin(k + \frac{1}{2})t \, dt \\
& \quad - \int_0^\pi \frac{\phi_x(t)}{\sin \frac{1}{2}t} \sum_{q+q^\gamma < k < m+m^\gamma} g(q, k) \sin(k + \frac{1}{2})t \, dt \\
& \quad + \int_0^\pi \frac{\phi_x(t)}{\sin \frac{1}{2}t} \sum_{q-q^\gamma \leq k \leq m-m^\gamma} g(q, k) \sin(k + \frac{1}{2})t \, dt \\
& = D_1 + D_2 + D_3 + D_4. \tag{3.7}
\end{aligned}$$

First,

$$\begin{aligned}
|D_3| & \leq \int_0^\pi \frac{|\phi_x(t)|}{t} \sum_{q+q^\gamma < k \leq m+m^\gamma} g(q, k) |\sin(k + \frac{1}{2})t| \, dt \\
& = O\{\sqrt{q} \exp(aq^{2\gamma-1})\}. \tag{3.8}
\end{aligned}$$

Similarly

$$|D_4| = O\{\sqrt{q} \exp(-aq^{2\gamma-1})\}. \tag{3.9}$$

For $q < m \leq k \leq m + m^\gamma$ we have

$$0 \leq (k - m)/\sqrt{m} < (k - q)/\sqrt{q} < (k - n)/\sqrt{n}.$$

Now (cf. Ikeno⁴, p.259)

$$|g(q, k) - g(m, k)| = O\left\{g(m, k) \left(\frac{(k - m)^2}{m^2} + \frac{|k - m|}{m} + \frac{1}{m} \right)\right\}. \tag{3.10}$$

Using (3.10) and the condition (1.10) on ω , we get

$$|D_1| = O\left\{ \int_0^\pi \frac{|\phi_x(t)|}{t} \sum_{m \leq k \leq m+m^\gamma} g(m, k) \left(\frac{(k - m)^2}{m^2} \right. \right. \\ \left. \left. \text{(equation contd. on p. 381)} \right) \right\}$$

$$\begin{aligned}
 & + \left(\frac{|k-m|}{m} + \frac{1}{m} \right) \times \left| \sin \left(k + \frac{1}{2} \right) t \right| dt \Big\} \\
 & = O \left\{ \int_0^{1/m} \frac{|\phi_x(t)|}{t} dt + \sum_{m \leq k \leq m+m^\gamma} g(m, k) \left(\frac{(k-m)^2}{m^2} \right. \right. \\
 & \quad \left. \left. + \frac{|k-m|}{m} + \frac{1}{m} \right) \left(\left| k + m \right| + m + \frac{1}{2} \right) t dt \right\} \\
 & \quad + O \left\{ \int_{1/m}^{\pi} \frac{|\phi_x(t)|}{t} dt + \sum_{m \leq k \leq m+m^\gamma} g(m, k) \left(\frac{(k-m)^2}{m^2} \right. \right. \\
 & \quad \left. \left. + \frac{|k-m|}{m} + \frac{1}{m} \right) dt \right\} \\
 & = O \left\{ \sqrt{m} \int_{1/m}^{1/m} |\phi_x(t)| dt \right\} + O \left\{ \frac{1}{\sqrt{m}} \int_{1/m}^{\pi} \frac{|\phi_x(t)|}{t} dt \right\} \\
 & = O \left(\omega \left(\frac{1}{m} \right) \right). \quad \dots (3.11)
 \end{aligned}$$

If $k \leq n < q < m$, we have

$$(k-m)/\sqrt{m} < (k-q)/\sqrt{q} < (k-n)/\sqrt{n} \leq 0$$

and (cf. Ikeno⁴, p. 260)

$$|g(q, k) - g(m, k)| = O \left\{ g(n, k) \left(\frac{(k-n)^2}{n^2} + \frac{|k-n|}{n} + \frac{1}{n} \right) \right\}.$$

Using this and arguing analogous to the estimation of D_1 we get

$$|D_2| = O \left(\omega \left(\frac{1}{m} \right) \right). \quad \dots (3.12)$$

Theorem 1 follows from (3.1) to (3.12) in view of (2.6) and (2.7).

Proof of Theorem 2—With ρ and θ defined in (2.14) we have

$$\begin{aligned}
 S_{\beta}^p(x) - f(x) &= \frac{1}{\pi} \int_0^{\pi} \frac{\phi_x(t)}{\sin \frac{1}{2}t} \sum_{k=0}^{\infty} (1+\beta)^{p+1} \binom{p-k}{p} \beta^k \\
 &\quad \times \sin \left(k + \frac{1}{2} \right) t dt \\
 &= \frac{1}{\pi} \int_0^{\pi} \frac{\phi_x(t)}{\sin \frac{1}{2}t} \operatorname{Im} \left\{ e^{it/2} \frac{(1-\beta)^{p+1}}{(1-\beta e^{it})^{p+1}} \right\} dt
 \end{aligned}$$

(equation continued on p. 282)

$$\begin{aligned}
&= \frac{1}{\pi} \int_0^{\pi} \frac{\phi_x(t)}{\sin \frac{1}{2}t} \left(\frac{1-\beta}{\rho} \right)^{p+1} \sin((p+1)\theta + \frac{1}{2}t) dt \\
&= \frac{1}{\pi} \left(\int_0^{a(p)} + \int_{a'(p)}^{b(p)} + \int_{b(p)}^{\pi} \right) \frac{\phi_x(t)}{\sin \frac{1}{2}t} \left(\frac{1-\beta}{\rho} \right)^{p+1} \\
&\quad \times \sin((p+1)\theta + \frac{1}{2}t) dt \\
&= \chi_1 + \chi_2 + \chi_3. \dots(3.13)
\end{aligned}$$

Now, using the fact that $(1-\beta) \leq \rho$ as also lemma 3 (i), we have

$$\begin{aligned}
|\chi_1| &= O \left\{ \int_0^{a(p)} \frac{|\phi_x(t)|}{t} \left(\frac{1}{2}t + (p+1)(Ct^3 + \frac{\beta t}{1-\beta}) \right) dt \right\} \\
&= O \left\{ p \int_0^{a(p)} t^{\alpha} dt \right\} \\
&= O(p^{-\alpha}).
\end{aligned}$$

By applying Lemma 3 (ii) to χ_3 and arguing similar to the estimation of J_3 in Lemma 2, we get

$$\begin{aligned}
|\chi_3| &= O \left\{ \int_{b(p)}^{\pi} \frac{|\phi_x(t)|}{t} \exp(-A(p+1)t^2) dt \right\} \\
&= O \left\{ \int_{b(p)}^{\infty} \frac{1}{t} \exp(-A(p+1)t^2) dt \right\} \\
&= O \left\{ \int_{A(p+1)[b(p)]^2}^{\infty} \frac{1}{u} e^{-u} du \right\} \\
&= O \{ p^{2\delta-1} \exp(-A(p+1)[b(p)]^2) \} \\
&= O(p^{-\alpha}).
\end{aligned}$$

χ_2 can be estimated exactly like the ' η_2 ' in the context of Taylor means treated by Chui and Holland¹ (pp. 35-37). We omit the details.

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A MODEL FOR MICROPOLAR FLUID FILM MECHANISM WITH REFERENCE TO HUMAN JOINTS

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This paper analyses the variation of pressure and load capacity with reference to load bearing human joints by introducing a continuously varying porosity model for lower plate instead of usual uniform mono or multi-layered models studied so far. A micropolar fluid film is taken as a lubricant. By suitable choice of non-dimensional porosity variation parameter $\bar{\alpha}$; it is shown that trends of variations are fairly in agreement with those recorded in earlier investigations.

NOTATION

a = Characteristic length of bearing,

β = film thickness,

β_0 = initial film thickness,

$\bar{\beta}$ = dimensional film thickness, β/β_0

α = porosity parameter of variation

$\bar{\alpha}$ = non-dimensional porosity parameter of variation, $a\alpha$

H = thickness of cartilage,

K_0 = porosity of cartilage,

\bar{K}_0 = dimensionless porosity parameter, K_0/β_0^2

l = $(\gamma/4\mu)^{1/2}$

L = β_0/l

N = coupling number $(\chi/(2\mu + \chi))^{1/2}$

p = pressure in fluid film region

\bar{p} = non-dimensional pressure in fluid film region, $2p\beta_0^3/\mu\nu a^2$,

u, v = velocity components in fluid film region,

\bar{u}, \bar{v} = velocity components in porous matrix,

v = velocity of approach,

W = load capacity,

\bar{W} = dimensionless load capacity $3W \beta_0^2 / \mu v a^3$,

x = x -coordinate

y = y -coordinate

μ = Newtonian viscosity coefficient

γ, χ = viscosity coefficient for micropolar fluid,

v = micro-rotation velocity.

1. INTRODUCTION

Within the last five decades sufficient thought has been given to the study of lubrication mechanism in human joints but the recent studies have brought out a fairly clear picture of this process. The human joint may be visualised as a class of mechanical bearing because the fluid in the cavity between two mating bones is believed to act as lubricant. The human joints in this context may be described as a system consisting of two mating bones covered with cartilage with synovial fluid between them. Jones¹ observed that a fluid film region was predominant mode of lubrication mechanism. The studies of Ogston and Stanier² have brought out the visco-elastic character of the synovial fluid. Various types of lubrication mechanism are believed to occur in the human joints like hydrodynamic³, boundary⁴, weeping⁵ and mixed lubrication⁶. Dintenfass⁷ found that synovial fluid is non-Newtonian due to the presence of hyaluronic acid (a long chain polymer) molecules and its viscosity decreases with increasing shear rate. This view was experimentally supported by Bloch and Dintenfass⁸, Maroudas⁹ and Dowson¹⁰. Further more the studies of Dowson¹⁰ and Mow¹¹ confirmed that the synovial fluid acts as lubricant. Eringen¹² formulated the theory of micropolar fluids, which has been used by many authors under various physical situations. As the micropolar fluid may be considered for polymers, it can be taken for the synovial fluid consisting a long chain polymers.

Cartilage is basically a two-phase deformable porous material which can absorb or give out fluid owing to the established pressure gradient by either squeeze film action of the synovial fluid or consolidation of the solid matrix by tissue deformation. The studies of Clark¹³, Torizilli and Mow^{14,15} have pointed out that cartilage is a three layered porous medium consisting of a superficial tangential zone, a middle zone and a deep zone. Nigam *et al.*¹⁶ investigated the effect of the variation of porosity in the

upper most layer of the cartilage which according to them plays a predominant role in the self adjusting nature of the human joint, taking a three layered porous medium. Sinha¹⁷ has considered the problem of lubrication of two approaching surfaces, one of which is covered with a layer of porous material and investigated the influence of porosity of the cartilage, film thickness, the thickness of the porous bad on axial pressure and load bearing capacity. He¹⁸ also investigated the influence of magnetic field on squeeze film lubrication with reference to human joints and noted that magnetotherapy can be of significant use in the treatment of diseases of human joints. Recently Tandon and Rakesh¹⁹ studied the lubrication mechanism occurring in knee joint replacement under restricted motion.

In this paper, the superficial division of cartilage matrix into three distinct layers is replaced by a continuously varying porosity matrix. The proposed model assumes flow of a fluid in a porous matrix of continuously varying porosity with a squeeze film of a micropolar fluid between two approaching surfaces. The mathematical analysis of the problem has been done by taking the continuity of pressure and velocities at the inter-face of the fluid film and the porous layer.

2. MATHEMATICAL FORMULATION

Referring to Fig. 1, the proposed model is conceived as a flow model of a squeeze film lubrication between two approaching surfaces with micropolar fluid and flow of

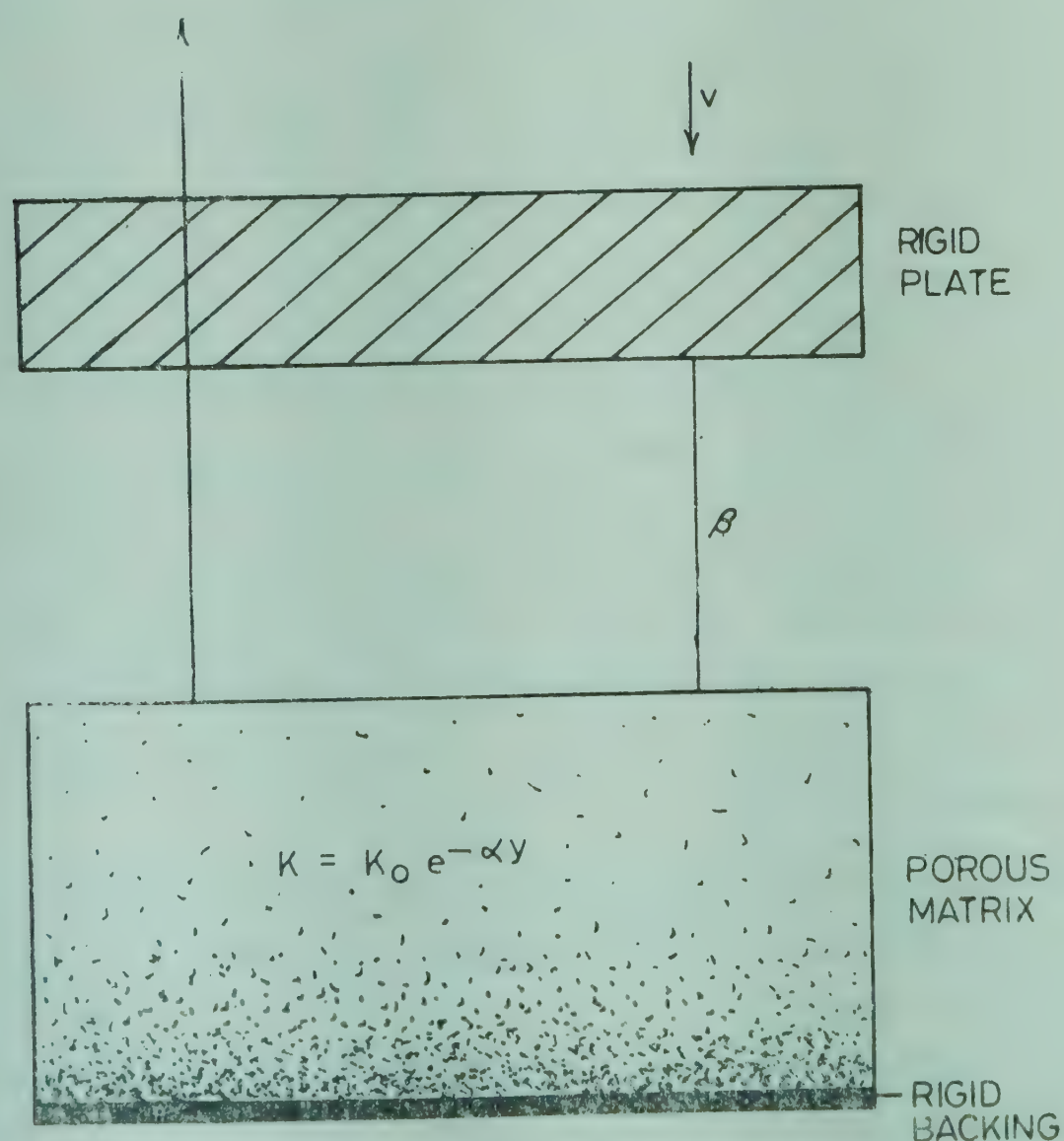


FIG. 1. Rectangular plate Model (synovial joint).

viscous fluid in a continuous porous matrix with variable porosity. The porous matrix is fixed and upper surface is rigid and moves with uniform velocity V in the negative direction of y -axis as shown in the Fig. 1.

2.1 Fluid Film Region

Following Eringen¹² the field equations for micropolar fluid may be reduced to the following form,

$$\frac{\partial^2 v}{\partial y^3} - m^3 \frac{\partial v}{\partial y} = \frac{m^2}{2\mu} \frac{\partial p}{\partial x} \quad \dots(1)$$

$$0 = \gamma \frac{\partial^2 v}{\partial y^2} - 2\chi v - \chi \frac{\partial u}{\partial y} \quad \dots(2)$$

and equation of continuity is

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad \dots(3)$$

where

$$m = \frac{N}{l} = \left(\frac{4\mu\chi}{\gamma(2\mu + \chi)} \right)^{1/2}$$

$$N = \left(\frac{\chi}{2\mu + \chi} \right)^{1/2} \text{ and } l = \left(\frac{\gamma}{4\mu} \right)^{1/2}.$$

2.2. Porous Region

Following Darcy's law the flow of a viscous fluid in a porous matrix is governed by

$$\bar{u} = - \frac{K}{\mu} \frac{d\bar{p}}{dx} \quad \dots(4)$$

$$\bar{v} = - \frac{K}{\mu} \frac{d\bar{p}}{dy} \quad \dots(5)$$

and equation of continuity is

$$\frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} = 0 \quad \dots(6)$$

where

$$K = K_0 e^{-\alpha y}.$$

2.3. Boundary conditions for Fluid Film

The boundary conditions in the fluid film region are

$$\left. \begin{aligned}
 p &= 0 \text{ at } x = \pm a \\
 v &= 0 \text{ at } y = 0, y = \beta \\
 u &= 0 \text{ at } y = \beta \\
 u &= \bar{u} \text{ at } y = 0 \\
 v &= \bar{v} \text{ at } y = 0 \\
 v &= V \text{ at } y = \beta
 \end{aligned} \right\} \dots(7)$$

and

2.4. Boundary Conditions for porous matrix

The boundary condition for porous matrix are

$$\bar{p} = 0 \text{ at } x = \pm a \dots(8)$$

and

$$\frac{\partial \bar{p}}{\partial y} = 0 \text{ at } y = -H. \dots(9)$$

2.5 Matching Condition

On the interface, $y = 0$,

$$p(x) = \bar{p}(x, 0). \dots(10)$$

3. SOLUTIONS

The geometry of the model and the frames of reference are shown in Fig. 1. In what follows the conventional assumptions of lubricant theory are assumed.

3.1. Porous region

The lubricant in the porous region is an incompressible Newtonian fluid. Using the value of \bar{u} and \bar{v} from eqns. (4) and (5) in eqn. (6) we get

$$\frac{\partial^2 \bar{p}}{\partial x^2} + \frac{\partial^2 \bar{p}}{\partial y^2} - \alpha \frac{\partial \bar{p}}{\partial x} = 0. \dots(11)$$

Integrating eqn. (10) with respect to y over the porous matrix thickness H , we get

$$\left(\frac{\partial \bar{p}}{\partial y} \right)_{y=0} = -H \frac{\partial^2 \bar{p}}{\partial x^2} + \alpha H \frac{\partial \bar{p}}{\partial x} \dots(12)$$

assuming that H is small.

3.2. Fluid Film Region of eqn. (1) under boundary conditions $v = 0$ at $y = 0, \beta$, is

$$\begin{aligned}
 v &= - \frac{C}{\sinh m\beta} \{ \sinh m\beta (\beta - y) - \sinh m\beta + \sinh my \} \\
 &\quad + \frac{1}{2\mu} \frac{dp}{dx} \left\{ \frac{\beta \sinh my}{\sinh m\beta} - y \right\}. \dots(13)
 \end{aligned}$$

Substituting this value of v in equation (2), we get

$$\begin{aligned} \frac{\partial u}{\partial y} = & \frac{y}{\mu} \frac{dp}{dx} - \frac{Dm\beta \sinh my}{2\mu \sinh m\beta} \frac{dp}{dx} \\ & - \frac{C}{\sinh m\beta} \{2 \sinh m\beta - Dm \sinh m(\beta - y) - Dm \sinh my\} \end{aligned} \quad \dots(14)$$

where

$$D = \frac{2}{m} - \frac{\gamma m}{\chi}.$$

Integrating eqn. (14) with respect to y , under boundary conditions we get

$$\begin{aligned} u = & \frac{y^2}{2\mu} \frac{dp}{dx} - \frac{K_0}{\mu} \frac{dp}{dx} + \frac{D\beta}{2\mu} \frac{dp}{dx} \frac{(1 - \cosh my)}{\sinh m\beta} \\ & - \frac{C}{\sinh m\beta} \{2y \sinh m\beta + D \cosh m(\beta - y) - D \cosh my \\ & - D (\cosh m\beta - 1)\} \end{aligned} \quad \dots(15)$$

where

$$C = - \frac{\frac{\beta}{2\mu} \frac{dp}{dx} \left\{ \sinh m\beta \left(\beta - \frac{2K_0}{\beta} \right) - D (\cosh m\beta - 1) \right\}}{2 \{D (\cosh m\beta - 1) - \beta \sinh m\beta\}}.$$

Integrating eqn (3) with respect to y we have

$$\frac{\partial}{\partial x} \int_0^\beta u dy = - \frac{K_0}{\mu} \left\{ -H \frac{d^2 p}{dx^2} + \alpha H \frac{dp}{dx} \right\} + V. \quad \dots(16)$$

Substituting the value of from eqn. (15) in eqn. (16) we get

$$\frac{d^2 p}{dx^2} + a_0 \frac{dp}{dx} = b_0 \quad \dots(17)$$

where

$$a_0 = - \frac{12 \alpha H K_0}{\beta \left\{ \beta^2 + 6 K_0 + \frac{12 H K_0}{\beta} + \frac{6D}{m} - 3D \beta \coth \frac{m\beta}{2} \right\}}$$

and

$$b_0 = - \frac{12 \mu v}{\beta \left\{ \beta^2 + 6 K_0 + \frac{12 H K_0}{\beta} + \frac{6D}{m} - 3D \beta \coth \frac{m\beta}{2} \right\}}.$$

On solving eqn (17) under boundary conditions, we get

$$p = \frac{b_0 a}{a_0} \left\{ -\coth a_0 a + \frac{\exp(-a_0 a \frac{x}{a})}{\sinh a_0 a} + \frac{x}{a} \right\}. \quad \dots(18)$$

3.3 Load

The load carrying capacity of the joint is given by

$$\begin{aligned} W &= \int_{-a}^a p dx \\ &= -\frac{2b_0 a}{a_0} \left\{ a \coth a_0 a = \frac{1}{a_0 a} \right\}. \end{aligned} \quad \dots(19)$$

4. NON-DIMENSIONALIZATION

Using following non-dimensional parameter

$$\begin{aligned} \bar{x} &= \frac{x}{a}, \quad \bar{\beta} = \frac{\beta}{\beta_0}, \quad L = \frac{\beta_0}{l}, \quad \bar{K}_0 = \frac{K_0}{\beta_0^2}, \quad \bar{H} = \frac{H}{\beta_0}, \\ \bar{p} &= \frac{2p\beta_0^3}{\mu\nu a^2}, \quad \bar{W} = \frac{3W\beta_0^3}{\mu\nu a^3}, \quad \bar{\alpha} = a\alpha, \quad \bar{a} = a_0 a, \quad \bar{b} = \frac{b_0\beta_0^3}{\mu\nu}. \end{aligned}$$

The non-dimensional pressure distribution is given by

$$\bar{p} = \frac{2\bar{b}}{\bar{a}} \left\{ -\coth \bar{a} + \frac{e^{\bar{a}\bar{x}}}{\sinh \bar{a}} + \bar{x} \right\}. \quad \dots(20)$$

The non-dimensional load carrying capacity is

$$\bar{W} = \frac{4\bar{b}}{\bar{a}} \left\{ \frac{1}{a} - \coth \bar{a} \right\} \quad \dots(21)$$

where

$$\bar{a} = -\frac{12\bar{\alpha}\bar{H}\bar{K}_0}{\bar{\beta} \left\{ \bar{\beta}^2 + 6\bar{K}_0 + \frac{12\bar{K}_0\bar{H}}{\bar{\beta}} + \frac{12}{L^2} - \frac{6N\bar{\beta}}{L} \coth \frac{NL\bar{\beta}}{2} \right\}}$$

and

$$\bar{b} = -\frac{12}{\bar{\beta} \left\{ \bar{\beta}^2 + 6\bar{K}_0 + \frac{12\bar{K}_0\bar{H}}{\bar{\beta}} + \frac{12}{L^2} - \frac{6N\bar{\beta}}{L} \coth \frac{NL\bar{\beta}}{2} \right\}}$$

5. DISCUSSION

To bring out the effects of change of shape and size of micromolecules and the concentration on bearing characteristics by using micropolar fluid as lubricant (as a substitute of synovial fluid) in a conjunction with influence of the porous nature of the cartilage. The micropolar fluid involves two dimensionless parameters N and L . Which do not occur in Newtonian theory and are called coupling number and material characteristic length respectively. In limiting cases as $N \rightarrow 0$ or $N \rightarrow \infty$, they consider with Newtonian cases provided μ is replaced by $(\mu + \frac{1}{2}\chi)$. Also a large value of l and small values of β_0 give rise to increase the effective viscosity and this is in line with the experimental evidence of Hanniker²⁰. Consequently the number L gives the influence of the shape and size of the suspended particles and N is a measure of the concentration of suspended particles.

Torzilli and Mow^{14,15} have given the following data of articular cartilage by considering a three layered model for the cartilage

$$\frac{K_1}{\mu} = 3 \times 10^{-13} \text{ cm}^4/\text{dyne} - \text{sec}$$

$$\frac{K_2}{\mu} = 6 \times 10^{-13} \text{ cm}^4/\text{dyne} - \text{sec}$$

$$\frac{K_3}{\mu} = 9 \times 10^{-13} \text{ cm}^4/\text{dyne} - \text{sec}$$

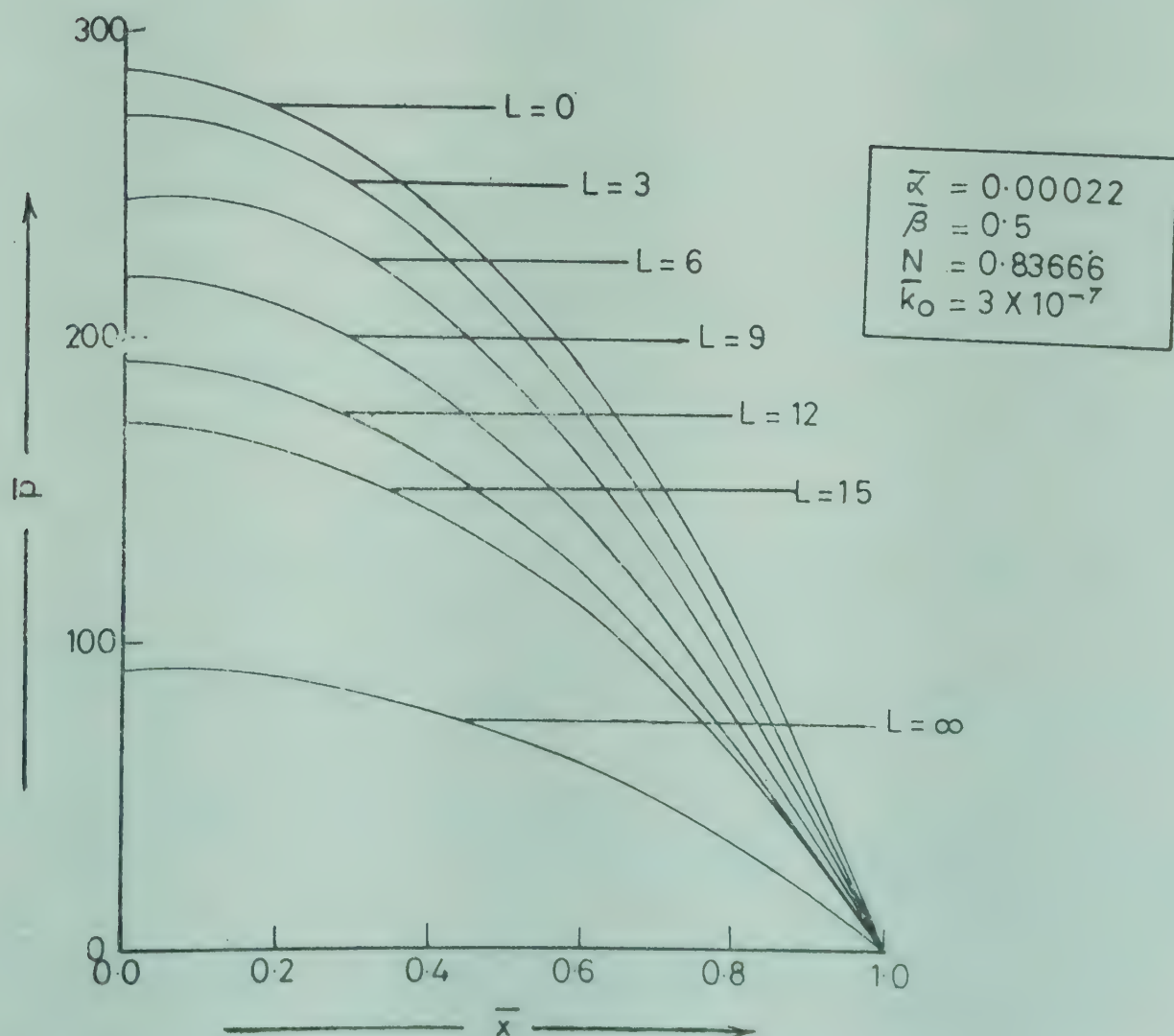


FIG. 2. Non dimensional axial pressure distribution for different values of shape and size index L .

$H_1 = 200$ microne, $H_2 = 0.2$ cm, $H_3 = 0.28$ cm and $\mu = 1$ poise.

Following Nigam *et al.*¹⁶ minimum film thickness $\beta_0 = 10^{-3}$ and upper surface porosity of the cartilage $K_0 = 3 \times 10^{-7}$. We have by assuming continuous variation in the porosity of the cartilage taken $H_1 + H_2 + H_3$ is 0.5 cm and have introduced a non-dimensional porosity parameter of variation $\bar{\alpha} = 0.00022$. Since exact data for quantities N and L for synovial fluid is not known we have chosen some values for these quantities.

In Fig. 2 the variation of non-dimensional axial pressure \bar{p} is shown for different values of shape and size index L it is obvious that as L increases, axial pressure decreases i. e. when shape and size of hyaluronic acid molecules decreases, axial pressure also decreases.

Figure 3 shows that as porosity at the interface increases, pressure decreases and this happens at a faster rate. The case of $\bar{K}_0 = 0$ corresponds to the case of non-

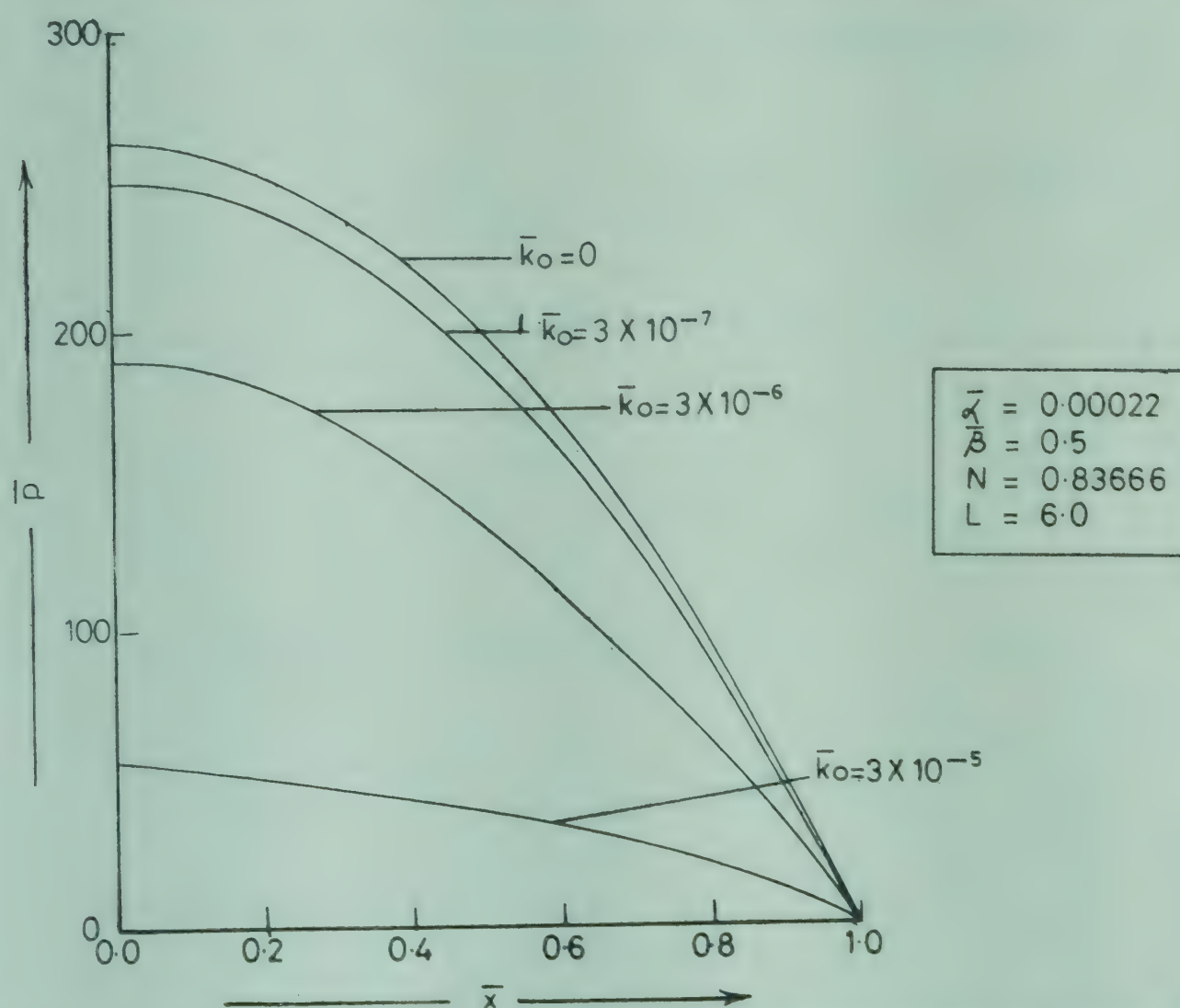


FIG. 3. Non dimensional axial pressure distribution for different values of porosity of superficial tangential layer.

porous cartilage for which the pressure is maximum. These results are in agreement with the observation of Prakash and Sinha²¹.

In Fig. 4 the variation of non-dimensional load bearing capacity \bar{W} with the film thickness $\bar{\beta}$ for different values of the porosity of the interface is shown. It is noted that the increase of film thickness, decreases the load bearing capacity \bar{W} and

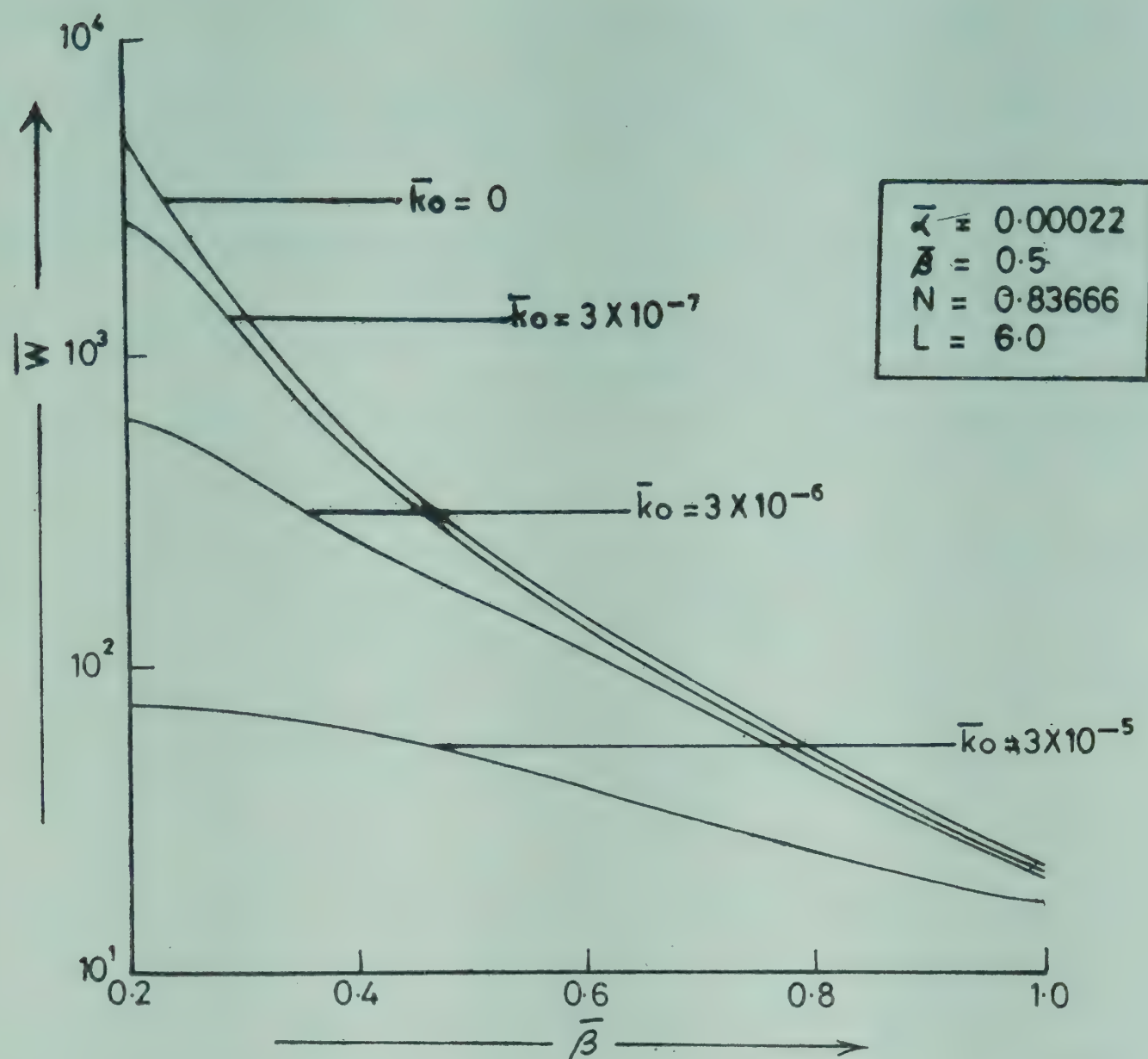


FIG. 4. Variation of non dimensional load carrying capacity \bar{w} with film thickness $\bar{\beta}$ for different values of porosity \bar{k}_0 .

the increase of interface porosity K_0^- , decreases \bar{W} . It is interesting to note that by choosing porosity parameter of variation $\bar{\alpha} = .00022$ we have obtained \bar{p} and \bar{W} which are in close agreement with those given by Nigam *et al.*¹⁶. Thus exponential law of variation of porosity as assumed here is quite efficient to replace a three layered porous matrix by a continuously varying porosity matrix.

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ON THE REGION FOR LINEAR GROWTH RATE IN ROTATORY HYDROMAGNETIC THERMOHALINE CONVECTION PROBLEM

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The present paper is an improvement of the results of Gupta *et al.*¹ concerning bounds for the linear growth rate of a disturbance in rotatory hydromagnetic thermohaline convection problems of Veronis² and Stren's³ type. As a consequence, the results of Banerjee *et al.*⁴ for thermohaline convection and rotatory thermohaline convection problem and of Gupta *et al.*⁵ for hydromagnetic thermohaline convection problem are also improved.

1. INTRODUCTION

The thermohaline convection problem has been extensively studied in the recent past under a variety of externally imposed force fields on account of its interesting complexities as a double diffusive phenomenon as well as its direct relevance to many problems of practical interest in the fields of oceanography, astrophysics and chemical engineering etc. The derivation of bounds for the linear growth rate of a disturbance in thermohaline convection problems is an important problem especially when the boundaries are rigid for in this case numerical solutions are most commonly used but they are also laborious. In this situation, derivation of certain integral estimates acquire great importance for they enable one to obtain sufficient conditions of stability and define a possible range of parameters for growing perturbations in case of instability⁶. Banerjee *et al.*⁴ and Gupta *et al.*^{1,5}, investigated in the recent past the thermohaline convection problems and derived bounds for the linear growth rate of an arbitrary oscillatory perturbation, neutral or unstable. However, in deriving these results, some positive definite integrals have been dropped and as a consequence some parameters of the problem which were there in the original equations do not occur in the resulting inequalities. Therefore, by making use of suitable estimates for the dropped terms one could possibly derive results which would contain the dropped parameters and improve upon the results of Banerjee *et al.*⁴ and Gupta *et al.*^{1,5}. The present paper is precisely in this direction.

2. GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

The governing nondimensional linearized perturbation equations for Veronis' thermohaline configuration in the presence of a uniform vertical rotation and magnetic field are given by (Gupta *et al.*¹):

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$$(D^2 - a^2) (D^2 - a^2 - \frac{p}{\sigma}) W + Q D (D^2 - a^2) h_z = R_T a^2 \theta - R_S a^2 \Phi + TDZ \quad \dots(1)$$

$$(D^2 - a^2 - p) \theta = -W, \quad \dots(2)$$

$$(D^2 - a^2 - \frac{p}{\tau}) \Phi = -\frac{W}{\tau} \quad \dots(3)$$

$$(D^2 - a^2 - \frac{p\sigma_1}{\sigma}) h_z = -DW \quad \dots(4)$$

$$(D^2 - a^2 - \frac{p}{\sigma}) Z = -QDX - DW \quad \dots(5)$$

$$(D^2 - a^2 - \frac{p\sigma_1}{\sigma}) X = -DZ \quad \dots(6)$$

with the boundary conditions

$$W = 0 = \theta = \Phi = DW = Z = h_z = DX \text{ at } z = 0 \text{ and } z = 1 \quad \dots(7)$$

(both the boundaries are rigid and perfectly conducting).

In the above equations the vertical coordinate z has the range $0 \leq z \leq 1$, $D \equiv d/dz$, a^2 is the square of the wave number, $p = p_r + ip_i$ is the complex growth rate, σ is the thermal Prandtl number, R_T is the thermal Rayleigh number, R_S is the concentration Rayleigh number, Q is the Chandrasekhar number, T is the Taylor number, τ is the ratio of mass diffusivity to heat diffusivity, σ_1 is the magnetic Prandtl number, W is the vertical velocity, h_z is the vertical magnetic field, θ is the temperature, Φ is the concentration, Z is the vertical vorticity and X is the vertical current density. Further, the governing equations and the boundary conditions for Stern's thermohaline configuration with a uniform vertical rotation and magnetic field are given by eqns. (1)–(7) with $R_T < 0$ and $R_S < 0$.

3. MATHEMATICAL ANALYSIS

We prove the following theorems :

Theorem 1— If $(p, W, \theta, \Phi, h_z, Z, X)$, $p = p_r + ip_i$, $p_r \geq 0$, $p_i \neq 0$, is a solution of eqns. (1) – (7) then

$$(p_r + \lambda \pi^2)^2 + p_i^2 < \alpha + \lambda^2 \pi^4 \quad \dots(8)$$

where

$$\lambda = \min(\tau, \frac{\sigma}{\sigma_1}) \text{ or } \min(\tau, \sigma) \text{ according as } \sigma_1 \geq 1 \text{ or } \sigma_1 < 1 \text{ respectively} \quad \dots(9)$$

ctively

$$\alpha = \max \left[R_S \sigma, \left(\frac{B + \sqrt{B^2 + 4C}}{2} \right)^2 \right] \quad \dots(10)$$

$$B = Q\sigma \text{ and } C = T\sigma^2(1 + Q)(1 + Q/\pi^4). \quad \dots(11)$$

PROOF : Multiplying eqn. (1) by W^* (the complex conjugate of W), integrating over the vertical range of z and proceeding as in Gupta *et al.*¹, we have for $p_i \neq 0$

$$\begin{aligned} & \frac{1}{\sigma} \int_0^1 (|DW|^2 + a^2 |W|^2) dz + R_T a^2 \int_0^1 |\theta|^2 dz + \frac{QT\sigma_1}{\sigma} \int_0^1 |X|^2 dz \\ &= \frac{Q\sigma_1}{\sigma} \int_0^1 (|Dh_z|^2 + a^2 |h_z|^2) dz + R_S a^2 \int_0^1 |\phi|^2 dz \\ &+ \frac{T}{\sigma} \int_0^1 |Z|^2 dz. \quad \dots(12) \end{aligned}$$

Multiplying eqns. (3) – (5) respectively by their complex conjugates, integrating over the range of z by parts repeatedly and utilizing the boundary conditions (7), we get

$$\begin{aligned} & \int_0^1 |(D^2 - a^2)\Phi|^2 dz + \frac{|p|^2}{\tau^2} \int_0^1 |\Phi|^2 dz + \frac{2p_r}{\tau} \int_0^1 (|D\Phi|^2 \\ &+ a^2 |\Phi|^2) dz = \frac{1}{\tau^2} \int_0^1 |W|^2 dz \quad \dots(13) \end{aligned}$$

$$\begin{aligned} & \int_0^1 |(D^2 - a^2)h_z|^2 dz + \frac{|p|^2 \sigma_1^2}{\sigma^2} \int_0^1 |h_z|^2 dz + \frac{2p_r \sigma_1}{\sigma} \int_0^1 (|Dh_z|^2 \\ &+ a^2 |h_z|^2) dz = \int_0^1 |DW|^2 dz \quad \dots(14) \end{aligned}$$

and

$$\begin{aligned} & \int_0^1 |(D^2 - a^2)Z|^2 dz + \frac{|p|^2}{\sigma^2} \int_0^1 |Z|^2 dz + \frac{2p_r}{\sigma} \int_0^1 (|DZ|^2 \\ &+ a^2 |Z|^2) dz = \int_0^1 |DW|^2 dz + Q^2 \int_0^1 |DX|^2 dz \\ &+ 2Q \operatorname{Re} \left(\int_0^1 DX DW^* dz \right) \quad \dots(15) \end{aligned}$$

where 'Re' denotes the real part.

Since $p_r \geq 0$, it follows from eqns. (13) — (15) that

$$\frac{|p|^2}{\tau^2} \int_0^1 |\Phi|^2 dz + \frac{2p_r}{\tau} \int_0^1 |D\Phi|^2 dz < \frac{1}{\tau^2} \int_0^1 |W|^2 dz \quad \dots(16)$$

$$\int_0^1 |(D^2 - a^2) h_z|^2 dz < \int_0^1 |DW|^2 dz \quad \dots(17)$$

$$\frac{|p|^2 \sigma_1^2}{\sigma^2} \int_0^1 |h_z|^2 dz + \frac{2p_r \sigma_1}{\sigma} \int_0^1 |Dh_z|^2 dz < \int_0^1 |DW|^2 dz \quad \dots(18)$$

and

$$\begin{aligned} \frac{|p|^2}{\sigma^2} \int_0^1 |Z|^2 dz + \frac{2p_r}{\sigma} \int_0^1 |DZ|^2 dz &< \int_0^1 |DW|^2 dz \\ &+ Q^2 \int_0^1 |DX|^2 dz + 2Q \operatorname{Re} \left(\int_0^1 DX DW^* dz \right). \end{aligned} \quad \dots(19)$$

By using the Rayleigh-Ritz inequality⁷, we have

$$\int_0^1 |\Phi|^2 dz \leq \frac{1}{\pi^2} \int_0^1 |D\Phi|^2 dz \quad \dots(20)$$

since $\Phi(0) = 0 = \Phi(1)$.

Similarly,

$$\int_0^1 |h_z|^2 dz \leq \frac{1}{\pi^2} \int_0^1 |Dh_z|^2 dz \quad \dots(21)$$

and

$$\int_0^1 |Z|^2 dz \leq \frac{1}{\pi^2} \int_0^1 |DZ|^2 dz. \quad \dots(22)$$

It now follows from inequalities (17), (18) and (19) that

$$\int_0^1 |\Phi|^2 dz < \frac{1}{(|p|^2 + 2p_r \tau \pi^2)} \int_0^1 |W|^2 dz \quad \dots(23)$$

$$\int_0^1 |h_z|^2 dz \leq \frac{\sigma^2}{(\sigma_1^2 |p|^2 + 2p_r \sigma \sigma_1 \pi^2)} \int_0^1 |W|^2 dz, \quad \dots(24)$$

and

$$\begin{aligned} \int_0^1 |Z|^2 dz &< \frac{\sigma^2}{(|p|^2 + 2p_r \sigma \pi^2)} \left[\int_0^1 |DW|^2 dz + Q^2 \int_0^1 |DX|^2 dz \right. \\ &\quad \left. + 2Q \operatorname{Re} \left(\int_0^1 DX DW^* dz \right) \right]. \quad \dots(2.5) \end{aligned}$$

Now,

$$\begin{aligned} \int_0^1 (|Dh_z|^2 + a^2 |h_z|^2) dz &= - \int_0^1 h_z (D^2 - a^2) h_z^* dz \\ &\leq \int_0^1 |h_z| | (D^2 - a^2) h_z^* | dz \\ &\leq \left\{ \int_0^1 |h_z|^2 dz \right\}^{1/2} \left\{ \int_0^1 |D^2 - a^2| h_z|^2 dz \right\}^{1/2} \end{aligned}$$

which, upon using inequalities (17) and (24), yields

$$\int_0^1 (|Dh_z|^2 + a^2 |h_z|^2) dz < \frac{\sigma}{\sigma_1 \left\{ |p|^2 + \frac{2p_r \sigma \pi^2}{\sigma_1} \right\}^{1/2}} \int_0^1 |DW|^2 dz. \quad \dots(26)$$

Multiplying eqn. (16) by X^* , integrating over the range of z by parts, utilizing the boundary conditions (7) and equating the real parts of the resulting equation, we get

$$\begin{aligned} \int_0^1 (|DX|^2 + a^2 |X|^2 + \frac{p \sigma_1}{\sigma} |X|^2) dz &= \operatorname{Re} \left(\int_0^1 X^* DZ dz \right) \\ &= \operatorname{Re} \left(- \int_0^1 Z DX^* dz \right). \quad \dots(27) \end{aligned}$$

Similarly, it follows from eqn. (5) that

$$\begin{aligned} \int_0^1 (|DZ|^2 + a^2 |Z|^2 + \frac{p_r}{\sigma} |Z|^2) dz &= \operatorname{Re} \left(\int_0^1 Z^* DW dz \right. \\ &\quad \left. + Q \int_0^1 Z^* DX dz \right) \quad \dots(28) \end{aligned}$$

Since $p_r \geq 0$, it follows from equation (27) that

$$\begin{aligned} \int_0^1 |DX|^2 dz &< \int_0^1 |Z| |DX| dz \\ &\leq \left\{ \int_0^1 |Z|^2 dz \right\}^{1/2} \left\{ \int_0^1 |DX|^2 dz \right\}^{1/2} \end{aligned}$$

or

$$\int_0^1 |DX|^2 dz < \int_0^1 |Z|^2 dz$$

from which

$$\int_0^1 |DX|^2 dz < \frac{1}{\pi^2} \int_0^1 |DZ|^2 dz \quad \dots(29)$$

can be obtained by using the inequality (22).

Now

$$\int_0^1 Z^* DX dz = - \int_0^1 X D Z^* dz$$

which upon using eqn. (6) gives

$$\operatorname{Re} \left(\int_0^1 Z^* DX dz \right) = - \int_0^1 (|DX|^2 + a^2 |X|^2 + \frac{p_r \sigma_1}{\sigma} |X|^2) dz < 0 \quad \dots(30)$$

since $p_r \geq 0$.

Equation (28), together with $p_r \geq 0$ and the inequality (30) implies that

$$\begin{aligned} \int_0^1 |DZ|^2 dz &< \operatorname{Re} \left(\int_0^1 Z^* DW dz \right) = \operatorname{Re} \left(- \int_0^1 W D Z^* dz \right) \\ &\leq \int_0^1 |W| |DZ| dz \\ &\leq \left\{ \int_0^1 |W|^2 dz \right\}^{1/2} \left\{ \int_0^1 |DZ|^2 dz \right\}^{1/2} \end{aligned}$$

so that

$$\begin{aligned} \int_0^1 |DZ|^2 dz &< \int_0^1 |W|^2 dz \\ &\leq \frac{1}{\pi^2} \int_0^1 |DW|^2 dz \quad (\text{Rayleigh-Ritz inequality}). \quad \dots(31) \end{aligned}$$

Combining the inequalities (29) and (31), we have

$$\int_0^1 |DX|^2 dz < \frac{1}{\pi^4} \int_0^1 |DW|^2 dz. \quad \dots(32)$$

Further,

$$\begin{aligned} \operatorname{Re} \left(\int_0^1 DX DW^* dz \right) &\leq \int_0^1 |DX| |DW| dz \\ &\leq \frac{1}{2} \int_0^1 (|DX|^2 + |DW|^2) dz. \end{aligned} \quad \dots(33)$$

Inequality (25), together with inequalities (32) and (33) gives

$$\int_0^1 |Z|^2 dz < \frac{\sigma^2 (1+Q) (1+Q/\pi^4)}{(|p|^2 + 2p_r \sigma \pi^2)} \int_0^1 |DW|^2 dz. \quad \dots(34)$$

Equation (12), together with the integral estimates (23), (26) and (34), gives

$$\begin{aligned} &\left[\frac{1}{\sigma} - \frac{Q}{\left\{ |p|^2 + \frac{2p_r \sigma \pi^2}{\sigma_1} \right\}^{1/2}} - \frac{T\sigma (1+Q) (1+Q/\pi^4)}{(|p|^2 + 2p_r \sigma \pi^2)} \right] \int_0^1 |DW|^2 dz \\ &+ a^2 \left[\frac{1}{\sigma} - \frac{R_S}{(|p|^2 + 2p_r \tau \pi^2)} \right] \int_0^1 |W|^2 dz \\ &+ R_T a^2 \int_0^1 |\theta|^2 dz + \frac{TQ\sigma_1}{\sigma} \int_0^1 |X|^2 dz < 0. \end{aligned} \quad \dots(35)$$

The inequality (35) clearly implies that if $\sigma_1 \geq 1$, then

either

$$\begin{aligned} &|p|^2 + 2p_r \tau \pi^2 < R_S \sigma, \\ \text{or} \\ &|p|^2 + \frac{2p_r \sigma^2 \pi}{\sigma_1} < \left(\frac{B + \sqrt{B^2 + 4C}}{2} \right)^2 \end{aligned} \quad \dots(36)$$

where B and C are as given by eqn. (11).

Taking $\lambda = \min(\tau, \frac{\sigma}{\sigma_1})$, it follows from (36) that

$$|p|^2 + 2p_r \lambda \pi^2 < \max \left[R_S \sigma, \left(\frac{B + \sqrt{B^2 + 4C}}{2} \right)^2 \right]$$

i. e.

$$(p_r + \lambda \pi^2)^2 + p_i^2 < \alpha + \lambda^2 \pi^4, \quad \dots(37)$$

where

$$\alpha = \max \left[R_S \sigma, \left(\frac{B + \sqrt{B^2 + 4C}}{2} \right)^2 \right].$$

Similarly, when $\sigma_1 < 1$, we get from the inequality (35) that

$$(p_r + \lambda \pi^2)^2 + p_i^2 < \alpha + \lambda^2 \pi^4 \quad \dots(38)$$

where now $\lambda = \min(\tau, \sigma)$.

This completes the proof of the theorem.

Note : It is to be noted that in the absence of rotation ($T = 0$), $\lambda = \min(\tau, \frac{\sigma}{\sigma_1})$, $\forall \sigma_1$ and in the absence of magnetic field ($Q = 0$), $\lambda = \min(\tau, \sigma)$.

Theorem 1—(i) shows that the linear growth rate $p (= p_r + i p_i)$ of an arbitrary oscillatory ($p_i \neq 0$) perturbation, neutral ($p_r = 0$) or unstable ($p_r > 0$), for rotatory hydromagnetic Veronis' thermohaline configuration, must lie inside a semicircle in the right half of the $p_r p_i$ -plane, whose centre is $(-\lambda \pi^2, 0)$ and $(\text{radius})^2 = \alpha + \lambda^2 \pi^4$. (ii) It indicates the stabilizing effect of λ since the semicircular region, in which the growth rate p lies, reduces with increasing values of λ . (iii) It gives a more rigid limitation on the growth rate (see Fig. 1) than that given by the semicircular region

$$|p|^2 = \max \left[R_S \sigma, \left(\frac{B + \sqrt{B^2 + 4C}}{2} \right)^2 \right]$$

of Gupta *et al.*¹.

Special cases of Theorem 1—It follows from Theorem 1 that

(i) for Veronis' thermohaline configuration (VTC, $Q = 0 = T$)

$$(p_r + \tau \pi^2)^2 + p_i^2 < R_S \sigma + \tau^2 \pi^4.$$

(ii) for rotatory VTC ($Q = 0$)

$$(p_r + \lambda \pi^2)^2 + p_i^2 < \alpha + \lambda^2 \pi^4$$

where

$$\alpha = \max(R_S \sigma, T \sigma^2) \text{ and } \lambda = \min(\tau, \sigma),$$

(iii) for hydromagnetic VTC ($T = 0$)

$$(p_r + \lambda \pi^2)^2 + p_i^2 < \alpha + \lambda^2 \pi^4,$$

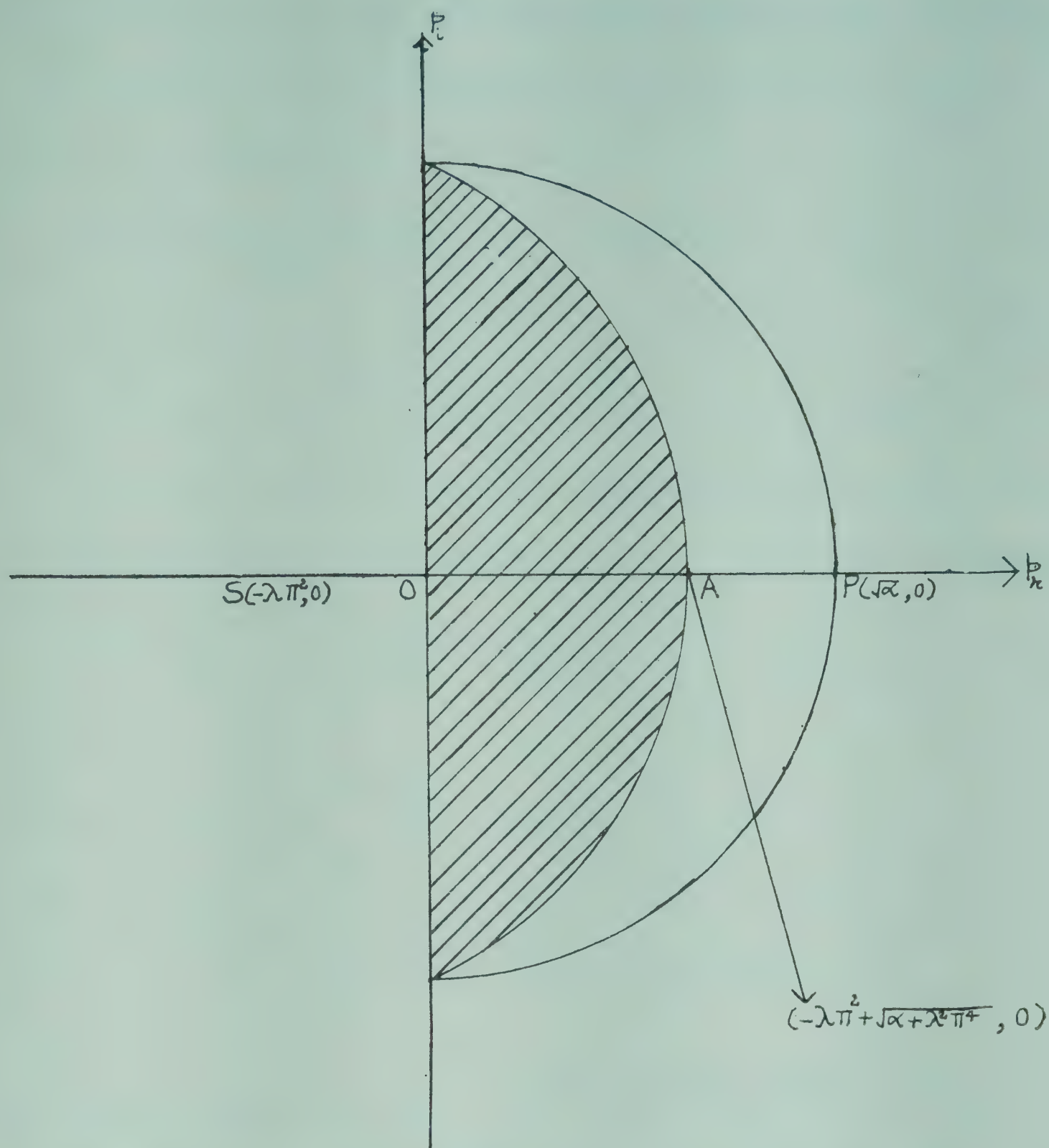


FIG. 1. Shaded area shows the modified region in which the complex growth rate of an arbitrary oscillatory perturbation, neutral or unstable, for rotatory hydromagnetic Veronis' thermo-haline configuration must lie.

Note : $\alpha + \lambda^2 \pi^4 < (\sqrt{\alpha} + \lambda \pi^2)^2$, so that $-\lambda \pi^2 + \sqrt{\alpha + \lambda^2 \pi^4} < \sqrt{\alpha}$, i. e. $OA < OP$.

where

$$\alpha = \max (R_S \sigma, Q^2 \sigma^2) \text{ and } \lambda = \min \left(\tau, \frac{\sigma}{\sigma_1} \right).$$

The above results give more rigid limitations on the linear growth rate of an arbitrary oscillatory perturbation, neutral or unstable, for VTC, rotatory VTC and hydromagnetic VTC than that given by the semicircular regions of Banerjee *et al.*⁴ and Gupta *et al.*⁵.

Theorem 2—If $(p, W, \theta, \Phi, h_z, Z, X)$, $p = p_r + i p_i$, $p_r \geq 0$, $p_i \neq 0$, is a solu-

tion of eqns. (1) – (7) with $R_T = 0$ and $R_S < 0$, then

$$(p_r + \hat{\lambda} \pi^2)^2 + p_i^2 < \hat{\alpha} + \hat{\lambda}^2 \pi^4 \quad \dots(39)$$

where

$$\hat{\lambda} = \min(1, \frac{\sigma}{\sigma_1}) \text{ or } \min(1, \sigma) \text{ according as } \sigma_1 \geq 1 \text{ or } \sigma_1 < 1 \quad \dots(40)$$

respectively,

$$\hat{\alpha} = \max \left[|R_T| \sigma, \left(\frac{B + \sqrt{B^2 + 4C}}{2} \right)^2 \right] \quad \dots(41)$$

and B and C are as given in Theorem 1.

PROOF : Putting $R_T = -|R_T|$ and $R_S = -|R_S|$ in eqn. (12), we have

$$\begin{aligned} & \frac{1}{\sigma} \int_0^1 (|DW|^2 + a^2 |W|^2) dz + \frac{QT\sigma_1}{\sigma} \int_0^1 |X|^2 dz \\ & + |R_S| a^2 \int_0^1 \int | \Phi |^2 dz = \frac{Q\sigma_1}{\sigma} \int_0^1 (Dh_z |^2 + a^2 |h_z|^2) dz \\ & + |R_T| a^2 \int_0^1 | \theta |^2 dz + \frac{T}{\sigma} \int_0^1 |Z|^2 dz. \end{aligned} \quad \dots(42)$$

Using the integral estimates (26), (34) and

$$\int_0^1 | \theta |^2 dz < \frac{1}{(|p|^2 + 2p_r \pi^2)} \int_0^1 |W|^2 dz \quad \dots(43)$$

which is derived in a manner similar to the derivation of (23), we get the result.

Theorem 2—(i) shows that the complex growth rate $p (= p_r + i p_i)$ of an arbitrary oscillatory perturbation, neutral or unstable, for rotatory hydromagnetic Stern's thermohaline configuration, must lie inside a semicircle, in the right half of the $p_r p_i$ -plane, whose centre is $(-\hat{\lambda} \pi^2, 0)$ and $(\text{radius})^2 = \hat{\alpha} + \hat{\lambda}^2 \pi^4$. (ii) It gives a more rigid limitation on the growth rate (see Fig. 2 which is essentially Fig. 1 with α, λ replaced by $\hat{\alpha}$ and $\hat{\lambda}$ respectively) then that given by the semicircular region

$$|p|^2 = \max \left[|R_T| \sigma, \left(\frac{B + \sqrt{B^2 + 4C}}{2} \right)^2 \right]$$

of Gupta *et al.*¹.

Special cases of Theorem 2—It follows from Theorem 2 that

(i) for Stern's thermohaline configuration (STC, $Q = 0 = T$)

$$(p_r + \pi^2)^2 + p_i^2 < |R_T| \sigma + \pi^4$$

(ii) for rotatory STC ($Q = 0$)

$$(p_r + \hat{\lambda} \pi^2)^2 + p_i^2 < \hat{\alpha} + \hat{\lambda}^2 \pi^4,$$

where

$$\hat{\alpha} = \max [|R_T| \sigma, T \sigma^2] \text{ and } \hat{\lambda} = \min (1, \sigma).$$

(iii) for hydromagnetic STC ($T = 0$)

$$(p_r + \hat{\lambda} \pi^2)^2 + p_i^2 < \hat{\alpha} + \hat{\lambda}^2 \pi^4$$

where

$$\hat{\alpha} = \max [|R_T| \sigma, Q^2 \sigma^2] \text{ and } \hat{\lambda} = \min (1, \frac{\sigma}{\sigma_1}).$$

The above results give more rigid limitations on the linear growth rate of an arbitrary oscillatory perturbation, neutral or unstable, for STC, rotatory STC and hydromagnetic STC than those given by the semicircular regions of Banerjee *et al.*³ and Gupta *et al.*⁵.

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CONTENTS

	<i>Page</i>
Combinatorial proofs of some enumeration identities <i>by</i> A. K. AGARWAL	313
A generalized variational inequality involving a gradient <i>by</i> J. PARIDA <i>and</i> MAKDAM SAHOO	319
Characterisations of extremally disconnected spaces <i>by</i> TAKASHI NOIRI	325
Splittings of Abelian groups by integers <i>by</i> V. K. GROVER	330
Cohomology and reducibility of representations of semisimple Γ -graded Lie Algebras <i>by</i> B. MITRA <i>and</i> K. C. TRIPATHY	333
(N, p, q) summability of Jacobi Series <i>by</i> S. P. KHARE <i>and</i> S. K. TRIPATHI	353
Approximation of a function by the $F(a, q)$ transform of its Fourier Series <i>by</i> M. S. RANGACHARI <i>and</i> S. A. SETTU	369
A model for micropolar fluid film mechanism with reference to human joints <i>by</i> S. P. SINGH, G. C. CHADDA <i>and</i> A. K. SINHA	384
On the region for linear growth rate in rotatory hydromagnetic thermohaline convection problem <i>by</i> J. R. GUPTA <i>and</i> M. B. KAUSHAL	395